



Fusion Power By Magnetic Confinement Program Plan

Volume III
Five Year Plan

Energy Research & Development Administration
Division Of Magnetic Fusion Energy

July 1976



DISCLAIMER

This Program Plan spells out the options available to the Division of Magnetic Fusion Energy under a range of possible funding assumptions called "Program Logics". As such, it represents a Division document and not necessarily the views of the top ERDA management. The Division believes, however, that the range of program logics and options presented will cover any eventualities which may arise in the course of setting program strategies with ERDA management, OMB, and Congress.

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FUSION POWER BY MAGNETIC CONFINEMENT
PROGRAM PLAN

VOLUME III

FIVE YEAR PLAN

JULY 1976

Prepared by the
Division of Magnetic Fusion Energy
U.S. Energy Research and Development Administration



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TABLE OF CONTENTS

	<u>PAGE</u>
I. GENERAL INTRODUCTION.....	1
A. Fusion Advantages.....	1
B. Program History.....	2
C. Long Range Planning Projections	3
D. Division Organization and Management	7
E. Organization of Reports.....	9
F. Foreign Efforts.....	11
G. Budget Summary.....	12
II. CONFINEMENT SYSTEMS	15
A. Introduction.....	15
B. Problem Areas.....	16
1. Tokamaks.....	16
2. Magnetic Mirror Systems.....	19
3. High Density Systems.....	22
C. Recent Achievements.....	27
1. Tokamaks.....	27
2. Magnetic Mirror Systems.....	33
3. High Density Systems.....	36
D. Program Structure and Major Milestones.....	39
1. Tokamaks.....	39
2. Magnetic Mirror Systems.....	42
3. High Density Systems.....	45
E. Budget Summary.....	49

	<u>PAGE</u>
III. TECHNICAL PROJECT OFFICE	53
A. Introduction.....	53
B. Tokamak Fusion Test Reactor.....	54
1. Introduction.....	54
2. Objectives.....	54
3. Principal Design Features.....	56
4. Project Milestones.....	58
5. Projected Budgets.....	59
C. Rotating Target Neutron Source.....	60
1. Introduction.....	60
2. Objectives.....	60
3. Principal Design Features.....	61
4. Project Milestones.....	61
5. Projected Budgets.....	62
D. Intense Neutron Source.....	62
1. Introduction.....	62
2. Objectives.....	63
3. Principal Design Features.....	64
4. Project Milestones.....	64
5. Projected Budgets.....	65
IV. DEVELOPMENT AND TECHNOLOGY PROGRAM	66
A. Introduction.....	66
B. Magnetic Systems.....	72
1. Magnetics.....	74
2. Energy Storage.....	81
C. Plasma Engineering.....	86
1. Neutral Beam Development.....	92
2. Alternate Heating Technology.....	100
3. Direct Energy Conversion.....	106
4. Vacuum Technology.....	111
5. Plasma Maintenance and Control.....	114
D. Fusion Reactor Materials	119
1. Alloy Development and Irradiation Performance.....	121
2. Plasma-Materials Interaction	129
3. Special Purpose Materials Development	135
4. Damage Analysis and Dosimetry	138
5. Radiation Facilities Development and Operation	141

	<u>PAGE</u>
E. Fusion Systems Engineering.....	147
1. Advanced Design.....	150
2. Systems Studies.....	156
3. Blanket and Shield Engineering.....	163
4. Tritium Processing and Control.....	172
5. Plasma Systems.....	179
6. Plant Systems.....	186
7. Environment and Safety.....	190
V. APPLIED PLASMA PHYSICS PROGRAM	200
A. Introduction.....	200
B. Problem Areas.....	202
1. Fusion Plasma Theory.....	202
2. Experimental Plasma Research.....	208
3. Computer Services and Technology.....	213
C. Recent Achievements.....	214
1. Fusion Plasma Theory.....	214
2. Experimental Plasma Research.....	221
3. Computer Services and Technology.....	230
D. Program Structure, Budget Summary and Milestones.....	232
1. Fusion Plasma Theory.....	232
2. Experimental Plasma Research.....	238
3. Computer Services and Technology.....	249
4. Possible Future Experiments	250
E. Applied Plasma Physics Operating Budget Summary.....	252

I. GENERAL INTRODUCTION

A. Fusion Advantages

The presently-established program goal of the magnetic confinement fusion program is to DEVELOP AND DEMONSTRATE PURE FUSION CENTRAL ELECTRICAL POWER STATIONS FOR COMMERCIAL APPLICATIONS. The potential advantages of commercial fusion reactors would be:

- 1) An effectively inexhaustible supply of fuel -- at essentially zero cost on an energy production scale;
- 2) A fuel supply that is available from the oceans to all countries and therefore cannot be interrupted by other nations;
- 3) No possibility of nuclear runaway;
- 4) No chemical combustion products as effluents;
- 5) No afterheat cooling problem in case of an accidental loss of coolant;
- 6) No uses of weapons grade nuclear materials; thus no possibility of diversion for purposes of blackmail or sabotage;
- 7) Activated materials that may be produced would have relatively low biological hazard, and their handling and disposal can be readily managed.

B. Program History

The present program in magnetic confinement began in the early 1950's. During its early years, the research concentrated primarily on problems of plasma confinement and heating. By the late 1960's, solutions to these problems had progressed to the point where good plasma confinement was achieved in a number of different magnetic field configurations. These conditions were achieved in relatively small devices with plasmas at temperatures low in comparison with the temperature necessary for significant fusion to occur. Nevertheless, to achieve these results, it was necessary to develop, to a highly sophisticated state, not only the basic science of plasma physics but also a variety of supporting technologies including normal and superconducting magnetics, vacuum systems, particle beams, energy storage and plasma diagnostics.

During the early seventies the program initiated an expansion to extend the results of the 1960's to larger hotter plasmas which ultimately would be capable of sustaining fusion reactions. Extension of the physics results of the 1960's involves new domains of physics and considerable technological development. Nevertheless initial results on plasma confinement in intermediate-size devices at moderate temperatures have inspired renewed confidence that the scientific and engineering/technological problems of heating and confining a fusion plasma can be solved. Increased emphasis has therefore recently been placed upon the longer range aspects of fusion reactors.

C. Long Range Planning Projections

The Long Range Projections are discussed in a separate volume (Volume II). In that volume five separate plans called "PROGRAM LOGICS" are discussed which are constrained primarily by the level of funding. Within these program logics, examples of options are presented which follow from the degree of success in the physics and engineering. The present volume discusses the "near term" (next five years) of a single plan, the "Logic III Reference Option."

The Logic III plan is defined as

LOGIC III. AGGRESSIVE

The levels of effort in physics and engineering are expanded according to programmatic need assuming that adequate progress is evident. New projects are undertaken when they are scientifically justified. Many problems are addressed concurrently. Funding is ample but reasonably limited. (This program would be aimed at an operating demonstration reactor in the late 1990's.)

The following general assumptions were used in developing Logic III:

- Tokamaks are presently the most promising approach to achieving commercial fusion power.
- One Experimental Power Reactor (EPR) will precede the Demonstration Reactor (DEMO).

- The next step in the tokamak program will be based upon the physics and engineering/technology results available in 1979.
- Of the Alternate Concepts, mirrors currently are the most advanced; the next step in the mirror program (MX) will be taken in FY 1978 and the next step beyond that will be based upon the physics and engineering/technology results available in 1982.
- Theta Pinches and other alternate concepts are being explored to identify more promising reactor concepts with respect to physics, engineering and economics. The toroidal theta pinch is the most advanced of these; other alternate concepts are less developed but do demonstrate promise.
- A decision on the first major DT facility for the theta pinch or other alternate concept is based on the physics and engineering/technology results available in 1985.
- Supporting theory and experiment is available throughout the program and supporting facilities are built as required.
- Costs are calculated assuming that the tokamak program proceeds to the DEMO and that one Alternate Concept proceeds through an EPR.

The general features of the Logic III Reference Option are shown in Figure I-1. The present program consists of several small and medium-sized hydrogen experiments (most notably the ORMAK and Alcator Tokamaks, the 2XIIB Mirror, and the Scyllac Theta Pinch) and the larger PLT at Princeton which came into operation in December 1975. Two other large tokamaks, Doublet III at General Atomic and PDX at Princeton, are in fabrication and scheduled to operate in early 1978. The first DT burning Tokamak, the Tokamak Fusion Test Reactor (TFTR) is scheduled to operate in mid-1981. A large mirror experiment, called MX, has been proposed for operation in 1981.

Under a Logic III program each of these devices would be upgraded, primarily by adding more auxiliary heating power, to test physics scaling laws at higher temperature and higher power density (beta). In the mid- to late-1980's, large device(s) would be built assuming good results are obtained on earlier facilities. The next step in the tokamak line is assumed to be either a Prototype Experimental Power Reactor or an Ignition Test Reactor (PEPR/ITR). TFTR would be upgraded. An engineering test reactor (FERF/ETR) is assumed, which could be a tokamak. By the early 1990's an Experimental Power Reactor (EPR) would be built, which makes net electrical power with high reliability. This device would be followed by the Fusion Power Demonstration Reactor in 1998.

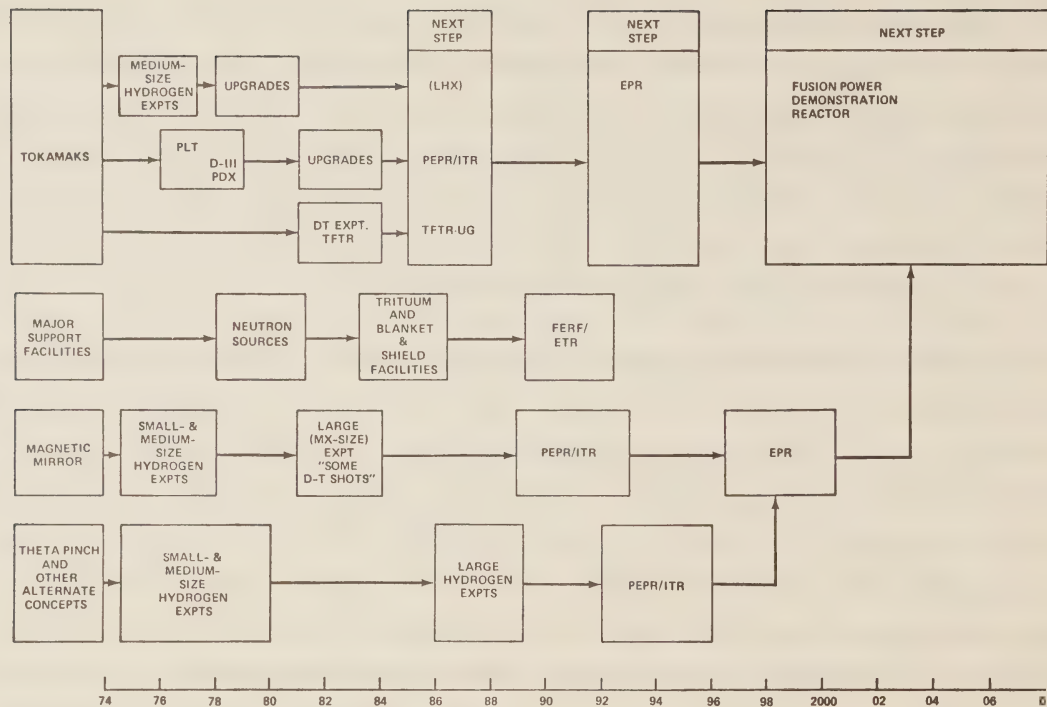


Figure I-1 General Features of the Logic III Reference Option

The Magnetic Mirror Program is assumed to evolve from the present small- and medium-size experiments, most notably 2XII at Livermore, to a larger device in which a limited number of DT shots would be possible. A major objective of this device would be to test confinement scaling for longer times, and to test methods for improving power balance, a prerequisite to the feasibility of a pure fusion mirror reactor. This would be followed by a PEPR device in the late 1980's. The FERF/ETR could be a mirror. This could be followed by an EPR operating in 1996 and a DEMO around 2004.

For the other Alternate Concepts, larger hydrogen experiments, such as the Large Staged Scyllac, are assumed to operate in the mid-1980's, followed by a PEPR/ITR in the early 1990's. Next could come an EPR in the late 1990's and a DEMO around 2007.

For costing purposes of Logic III, 3 PEPR/ITR devices; 1 FERF/ETR, 2 EPR's, and 1 DEMO are assumed.

D. Division Organization and Management

To manage the program, the Division of Magnetic Fusion Energy is organized into the following four interrelated programs:

- 1) Confinement Systems (CS) within which experiments are fabricated and operated to model many of the features of fusion reactors, in order to determine practical methods of achieving the conditions necessary for fusion reactors. Included within the Confinement Systems Program are all of the major tokamak, mirror and theta pinch experiments (with the exception of the construction of the Tokamak Fusion Test Reactor) and two other highly developed Alternate Concepts: the Z-pinch and the Elmo Bumpy Torus;
- 2) Technical Projects Office (TPO) which supervises the construction of the Tokamak Fusion Test Reactor and two neutron sources (RTNS and INS);
- 3) Development and Technology (D&T) within which solutions to the problems associated with the design and construction of the next generation of plasma confinement devices are developed and a broad technological base is developed in areas important to practical fusion power reactors. Included within the program are neutron radiation damage studies, superconducting magnet development, development of auxiliary heating systems and power supplies, systems studies and environmental safety;

- 4) Applied Plasma Physics (APP) within which theoretical and experimental studies of fusion-relevant plasmas are conducted, seeking the body of knowledge required to understand and predict the behavior of fusion experiments and the operating characteristics of fusion reactors. Applied Plasma Physics supports all of the Division's theoretical work including management of the computer facilities, the basic smaller experiments, diagnostic development, and the smaller and newer exploratory concepts.

The personnel of the Division are listed in Figure I-2.

E. Organization of Report

The present report is structured along the lines of the four programs discussed above. Each major section of the report is devoted to one of the four programs. In Section II the Confinement Systems Program is discussed. Problem areas are described followed by a discussion of recent achievements for Tokamaks, Magnetic Mirrors and High Density Systems. The present program structure and major milestones are then presented, followed by a five-year budget summary.

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Figure I-2

In Section III the activities of the Technical Projects Office are discussed. Three major construction projects are treated: the Tokamak Fusion Test Reactor (TFTR), the Rotating Target Neutron Source (RTNS) and the Intense Neutron Source (INS).

In Section IV the Development and Technology Program is discussed. Major development programs are described in four areas: Magnetic Systems, Plasma Engineering, Reactor Materials, and Fusion Systems Engineering.

In Section V the Applied Plasma Physics Program is discussed. Problem areas followed by a discussion of recent achievements are described for Fusion Plasma Theory, Experimental Plasma Research Computer Services and Technology. The present program structure and major milestones are then presented along with five-year budget requirements.

F. Foreign Efforts

Vigorous programs to develop fusion reactors also exist in the Soviet Union, Europe and Japan. The Soviets are planning a superconducting tokamak (T-10M) the size of PLT and a DT burning tokamak, the T-20, which is much larger than the TFTR.

The Euratom countries have formed a joint fusion development program, which is completing the design of a large experiment called the Joint European Tokamak (JET). The Japanese are planning a TFTR-sized Tokamak (JT-60). It is scheduled to operate in 1980. Mirror research is conducted in the Soviet Union, Japan and Sweden. There are high density programs in Britain, Germany, Japan, and Russia. High Density facilities projected are the High-Beta Stellarator, HBS-II, at Garching, and the Toroidal Z-Pinch, HBTX, at Culham. The U.S. program is approximately 1/3 of the total world effort, based upon total manpower.

G. Budget

A summary of the budget requirements for the years FY 1978-82 is shown in Figure I-3. FY 1976 and FY 1977 are shown for comparison. Budget detail is presented in Figure I-4. It should be noted that prior to the FY 1976 budget most major experiments in this program have been built using operating and equipment funds rather than as construction line items. This is reflected in the FY 1976-77 budgets, which include the fabrication of PLT at a cost of \$14 million, the PDX at a cost of \$18.8 million and the Doublet III at a cost of \$27.7 million.

	Fiscal Years (\$M)								Total 78-82
	1976	1976T	1977	1978	1979	1980	1981	1982	
<u>Operating Expenses</u>	<u>120.0</u>	<u>37.0</u>	<u>182.0</u>	<u>247.1</u>	<u>280.0</u>	<u>327.0</u>	<u>346.0</u>	<u>376.0</u>	<u>1576.1</u>
Confinement Systems	61.9	19.3	79.6	110.0	125.0	140.0	140.0	150.0	665.0
Technical Projects	0.4	0.8	10.0	18.0	12.0	22.0	25.0	25.0	102.0
Development & Technology ..	33.4	9.2	58.0	75.0	95.0	110.0	126.0	146.0	552.0
Applied Plasma Physics	24.3	7.7	34.4	44.1	48.0	55.0	55.0	55.0	257.1
Equipment	17.4	4.6	23.0	32.0	44.6	55.3	45.2	55.1	232.2
Construction	17.6	5.5	97.5	130.0	105.0	145.0	257.0	324.0	961.0
<u>TOTAL Magnetic Fusion Energy</u>	<u>155.0</u>	<u>47.1</u>	<u>302.5</u>	<u>409.1</u>	<u>429.6</u>	<u>527.3</u>	<u>648.2</u>	<u>755.1</u>	<u>2769.3</u>

Figure I-3
Summary Budget Projections

Figure I-4

Budget Detail

Fiscal Years (\$M)

	1976	1976T	1977	1978	1979	1980	1981	1982	Total 78-82
<u>Total Operation</u>	<u>120.0</u>	<u>37.0</u>	<u>182.0</u>	<u>247.1</u>	<u>280.0</u>	<u>327.0</u>	<u>346.0</u>	<u>376.0</u>	<u>1576.1</u>
<u>Confinement Systems</u>	<u>61.9</u>	<u>19.3</u>	<u>79.6</u>	<u>110.0</u>	<u>125.0</u>	<u>140.0</u>	<u>140.0</u>	<u>150.0</u>	<u>665.0</u>
Tokamaks	43.2	13.8	57.4	70.0	75.0	80.0	80.0	80.0	385.0
Mirror Systems	10.9	3.5	14.0	28.9	36.4	41.1	36.9	40.7	184.0
High Density Systems	7.8	2.0	8.2	11.1	13.6	18.9	23.1	29.3	96.0
<u>Technical Projects</u>	<u>0.4</u>	<u>0.8</u>	<u>10.0</u>	<u>18.0</u>	<u>12.0</u>	<u>22.0</u>	<u>25.0</u>	<u>25.0</u>	<u>102.0</u>
TFTR	0.4	0.8	10.0	15.3	10.3	20.0	23.0	25.0	93.6
RTNS	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	1.2
INS	0.0	0.0	0.0	1.5	1.7	2.0	2.0	0.0	7.2
<u>Development & Technology</u> ...	<u>33.4</u>	<u>9.2</u>	<u>58.0</u>	<u>75.0</u>	<u>95.0</u>	<u>110.0</u>	<u>126.0</u>	<u>146.0</u>	<u>552.0</u>
Magnetic Systems	7.4	1.9	17.7	19.0	25.0	28.0	32.1	37.2	141.3
Plasma Engineering	10.1	3.7	19.7	21.0	25.0	26.0	29.8	34.5	136.3
Fusion Reactor Materials .	6.9	1.7	9.3	16.0	20.0	23.0	26.3	30.5	115.8
Fusion Systems Eng.	8.6	1.8	10.3	18.0	23.0	30.0	34.4	39.9	145.3
Environ. and Safety	0.4	0.1	1.0	1.0	2.0	3.0	3.4	3.9	13.3
<u>Applied Plasma Physics</u>	<u>24.3</u>	<u>7.7</u>	<u>34.4</u>	<u>44.1</u>	<u>48.0</u>	<u>55.0</u>	<u>55.0</u>	<u>55.0</u>	<u>257.1</u>
Fusion Plasma Theory	12.3	3.6	13.6	17.7	21.0	25.0	25.0	25.0	113.7
Experimental Plasma Res. .	8.8	3.1	15.8	17.4	18.3	20.0	20.0	20.0	95.7
Comp. Services & Tech. ...	3.2	1.0	5.0	9.0	8.7	10.0	10.0	10.0	47.7
<u>Equipment</u>	<u>17.4</u>	<u>4.6</u>	<u>23.0</u>	<u>32.0</u>	<u>44.6</u>	<u>55.3</u>	<u>45.2</u>	<u>55.1</u>	<u>232.2</u>
Confinement Systems	7.7	2.5	8.2	16.2	17.4	17.3	18.5	20.4	89.8
Technical Projects	0.1	0.1	1.1	2.3	3.5	3.0	1.4	0.0	10.2
Development & Technology ...	5.2	1.0	5.7	8.5	15.3	16.0	19.2	20.0	79.0
Applied Plasma Physics	4.4	1.0	8.0	5.0	8.4	19.0	6.1	14.7	53.2
<u>Construction</u>	<u>17.6</u>	<u>5.5</u>	<u>97.5</u>	<u>130.0</u>	<u>105.0</u>	<u>145.0</u>	<u>257.0</u>	<u>324.0</u>	<u>961.0</u>
TFTR	15.0	5.5	80.0	95.0	35.0	15.0	35.0	35.0	215.0
PEPR/ITR	0.0	0.0	0.0	0.0	15.0	50.0	80.0	105.0	250.0
High Field Neutron Source ..	0.0	0.0	0.0	10.0	15.0	20.0	20.0	10.0	75.0
Tritium Facility	0.0	0.0	0.0	0.0	5.0	10.0	20.0	10.0	45.0
Blanket and Shield	0.0	0.0	0.0	0.0	0.0	5.0	10.0	20.0	35.0
RTNS	2.5	0.0	2.5	0.0	0.0	0.0	0.0	0.0	0.0
INS	0.1	0.0	15.0	10.0	0.0	0.0	0.0	0.0	10.0
Engineering Test Facilities.	0.0	0.0	0.0	0.0	0.0	10.0	32.0	39.0	81.0
MX	0.0	0.0	0.0	15.0	35.0	35.0	15.0	0.0	100.0
LSS	0.0	0.0	0.0	0.0	0.0	0.0	15.0	35.0	50.0
LHX (2)	0.0	0.0	0.0	0.0	0.0	0.0	30.0	70.0	100.0
<u>TOTAL</u>	<u>155.0</u>	<u>47.1</u>	<u>302.5</u>	<u>409.1</u>	<u>429.6</u>	<u>527.3</u>	<u>648.2</u>	<u>755.1</u>	<u>2769.3</u>

II. CONFINEMENT SYSTEMS

A. Introduction

The Confinement Systems subprogram is responsible for solving the experimental problems connected with the confinement of fusion plasma by magnetic fields. The goal of this program is to demonstrate long time confinement of high temperature plasmas at power-producing reactor conditions and to optimize the plasma physics aspects of fusion reactor systems.

The principal approach to the confinement of plasma is the tokamak which is a donut-shaped, long pulse time, moderate-density device. In addition, strong efforts are maintained in two other magnetic confinement concepts. These are magnetic mirror systems, including both open and toroidally linked mirror systems, and high density short pulsed systems, including the toroidal theta pinch, the straight theta pinch and the Z-pinch. Each of these approaches is believed capable of contributing to the major goal of a power producing, economic electrical power plant and/or to one or more of several other possible applications of fusion, e.g., materials testing reactors, fusion-fission hybrid reactors, fission product burners, production of fissionable material, etc.

The following sections present discussion of problem areas for each of the three approaches, recent achievements, program plans and budget requirements.

B. Problem Areas

Each of the three confinement systems approaches has unique problem areas, and each consists of experiments aimed at solving these problems.

1. Tokamaks

The major problem areas of the tokamak physics program are:

- Heating
- Transport and Scaling
- Plasma Shape Optimization
- Impurity Control and Boundary Effects
- Fueling

Heating refers to the process of producing the plasma temperatures necessary for a fusion reactor. Fusion reactors require ion and electron temperatures of about 10 keV. Electron temperatures of 1-2 keV and ion temperatures of 0.5-1.5 keV are typical of today's plasmas. Initial heating is provided by ohmic heating, which is produced by passing an electric current through the plasma. Additional heating by other methods is required to raise the temperature to that which will be

required for a reactor. Two methods are being tested: injection of beams of energetic neutral atoms and application of radio frequency power. Fusion reactors may require beam or rf powers of ~ 100 MW. Present day neutral beam experiments are performed with injected powers of ~ 0.3 MW, and a 4 MW beam system is being built for the Princeton Large Torus (PLT). The Tokamak Fusion Test Reactor (TFTR), scheduled for operation in 1981, will have an injected beam power of ~ 20 MW and will have some plasma compression capability as well. Heating with RF power is being tested at the 0.2 MW level in advance of a decision to proceed to higher power levels.

Transport and Scaling refers to the development of the physical laws which describe the measured transport of plasma energy in present experiments and the development of scaling laws to predict plasma behavior in larger, higher temperature devices. This area is, therefore, closely related to the heating program, and research on the two is conducted simultaneously. Fusion reactors are expected to have plasma radii of about 2-4m and plasma currents of about 10 MA. PLT, having begun operation in December 1975, is designed to operate with a plasma radius of ~ 0.5 m and a plasma current of ~ 1 MA; it will therefore provide an operating point between existing smaller plasmas and those of a reactor. Present theory predicts a significant change in the plasma transport as electron temperatures increase above 1-2 keV. The PLT experiment will explore the physics of this important regime. TFTR will have a plasma radius of ~ 1 m and a plasma current of ~ 2 MA.

Configurational Stability or Plasma Shape Optimization addresses the possibility, predicted by theory, that non-circular plasma shapes can be confined by lower strength magnetic fields and thus lead to lower fusion power plant costs. The techniques required are in use today on the Doublet IIA experiment, and definitive tests are scheduled on reactor grade plasmas in the Doublet III, beginning in 1978. Slightly elongated plasmas can also be studied on the Poloidal Divertor Experiment, beginning also in 1978.

Impurity Control and Boundary Effects refers to problems resulting from the interaction of the plasma with its material boundaries. These interactions can result in an influx of non-hydrogenic (impurity) atoms into the plasma, possibly cooling the plasma core directly and/or cooling the plasma edge, causing the plasma to shrink and become unstable. One method of reducing boundary effects will be tested in the Poloidal Divertor Experiment in which additional magnetic fields near the plasma edge will carry escaping particles away from the walls into special pumping regions.

Fueling refers to problems associated with replenishing plasma fuel in reactors with long burn times. This is a long range problem, but initial experiments are planned on PLT, PDX and ORMAK.

2. Magnetic Mirror Systems

In the Magnetic Mirror program, the major areas of investigation are open systems (minimum-B configurations) and toroidally-linked mirrors (EBT).

a. Minimum-B Mirrors

The major problem areas for the minimum-B (open) configurations are:

- confinement scaling
- Q-enhancement
- steady-state operation

Confinement scaling refers to the dependence of the confinement time τ , or more generally the Lawson parameter $n\tau$, on experimental variables such as the amount of warm plasma stream necessary to stabilize the drift cyclotron loss cone (DCLC) mode, the plasma dimensions (in units of the ion gyroradius) R/ρ_i and L/ρ_i , the plasma beta, the angle of neutral beam injection, etc. Classical theory predicts $n\tau \sim T_i^{3/2}$ in the absence of a stabilizing stream, as is predicted in the case of large experiments ($R/\rho_i \gtrsim 40$). This prediction needs to be tested experimentally at ion energies ≥ 50 keV. Present experiments are operating at ion energies up to 13 keV and with $R/\rho_i \simeq 2-3$. MX will have ion energies ~ 50 keV and $R/\rho_i \simeq 13$.

Q-enhancement refers to methods for improving the power balance in mirror fusion reactors (Q is a plasma quantity, defined as the ratio of thermonuclear power output to neutral-beam heating power input). Recent mirror reactor designs have been based on classical values of Q in the range of ~ 1.0 - 1.1 . These low Q values require stringent reactor engineering measures to yield net electrical power. A factor of 2-3 or more improvement in Q would greatly ease the technology requirements and reduce capital costs for mirror reactors.

Steady-state operation refers to the achievement of at least multi-second, high throughput vacuum pumping capability, neutral beam sources, and neutral beam power supplies. The multi-second operating regime is important because on this time scale the neutral particle reflux from the walls is predicted to reach an equilibrium rate. The ultimate goal of mirror fusion reactors is steady state operation.

b. Toroidally-linked mirrors (EBT)

The major problem areas for EBT are:

- plasma stability
- microwave heating
- confinement scaling

Plasma stability refers to the stability of the complex EBT confinement configuration of a toroidal loop within annular rings. MHD stability has been observed in EBT with low toroidal plasma density ($2\text{-}6 \times 10^{12} \text{cm}^{-3}$). However, the stability of projected operating densities ($\sim 10^{14} \text{cm}^{-3}$) needs to be investigated.

Microwave heating at millimeter wavelengths (ECR) is the method proposed for plasma heating in EBT. A clear understanding of ECR heating at higher densities ($> 10^{13} \text{cm}^{-3}$) is thus an important goal of the program.

Confinement scaling refers to the dependence of confinement time on plasma parameters (e.g., density, beta), the frequency and power of the microwave heating source, and the aspect ratio of the device. In a steady-state device, such as EBT, the particle and energy confinement times will depend on equilibrium transport properties. The critical-density limit set by the microwave frequency is important in this regard, since even at 120 GHz ($n_e \sim 2 \times 10^{14} \text{cm}^{-3}$), rather long energy confinement times (~ 1 sec) are required to exceed the Lawson criterion.

3. High Density Systems

In the High Density Systems Program, the major areas of investigation are the theta pinch and the Z-pinch. Theta pinch research is concerned with both linear and toroidal devices. Z-pinch research is presently conducted only in tori.

a. Toroidal Theta Pinch

In the toroidal theta pinch program, the major problem areas are:

- plasma confinement
- staged heating

Plasma confinement refers to the problem of creating a stable toroidal equilibrium for the theta-pinch-like plasma column in Scyllac. Equilibrium requires that the plasma column be formed initially in an approximate force balance near the center of the toroidal discharge tube. The plasma column should have the appropriate equilibrium surface distortion required by the presence of higher order multipole fields ($\ell = 0,1,2$) which, in addition to the usual theta pinch magnetic field B_0 , provide the toroidal force balance. Stability requires that the equilibrium plasma, once formed, remain confined in spite of small perturbations in

position. In the Scyllac experiments, this stability is achieved by means of a fast feedback stabilization system which drives $\ell = 2$ multipole windings. A more efficient stabilization technique, wall stabilization, is planned for theta pinch reactors, and will be tested in the Staged Theta Pinch (STP) experiment and on Staged Scyllac.

Staged heating refers to the separate application, or staging, of the two phases of heating in theta pinches: implosion (or shock) heating and adiabatic compression. Projected toroidal theta pinch experiments, such as Staged Scyllac and LSS, require separation and control of these two heating phases to achieve greater implosion heating and less adiabatic compression. The resulting "fat" plasma has a large ratio of plasma radius to wall radius, which is both economically advantageous for reactors and essential for effective stabilization of the $m = 1$ (sideward) mode by the wall.

b. Linear Theta Pinches

In the linear theta pinch program, the major problem areas are:

- end loss
- high field operation

End loss refers to the loss of both particles and energy (in the form of heat conduction) from the open ends of linear systems. Without some form of end-stoppering, plasma ions will stream out of the ends at roughly the ion thermal velocity. Without steps to correct this situation, a fusion reactor based on the linear theta pinch would be impractically long (many kilometers). A variety of flow barriers, both material and electromagnetic, are currently under investigation. Axial thermal conduction by electrons along field lines is a potential source of heat loss to the central plasma column, even in the absence of particle end loss, and studies to reduce this effect are in progress.

High field operation refers to the practical necessity of operating a linear fusion reactor at rather large values of the magnetic field. Since reactor length scales as B^{-2} , an increase in the magnetic field from, say, 50 kG to 500 kG, can yield dramatic reductions in reactor length requirements.

c. Z-Pinch

In the Z-pinch program, the major problem areas are:

- heating
- profile optimization

Heating refers to the process of achieving plasma temperatures relevant to a fusion reactor, i.e., ≥ 5 keV. Z-pinches are, in principle, capable of being heated to ignition by joule heating alone, without the addition of auxiliary heating techniques such as neutral beams or r.f. Shock heating may also play an important role in reaching ignition temperatures in Z pinches and is being studied.

Profile optimization refers to the tailoring of pressure and magnetic profiles to achieve MHD stability in the Z-pinch. Non-ideal MHD mechanisms, such as plasma transport in the form of diffusion and heat conduction will modify the programmed profiles. Confinement time, which has been diffusion limited in ZT-1, is predicted to scale with the square of the minor radius.

4. Summary

A summary of the critical problem areas and the key experimental programs addressing these problems is shown in Figure II-1. Note that many of the experiments are designed to address more than one critical problem.

Critical Problem Area

Key Experiments

Tokamaks

- Heating
- Transport and Scaling
- Plasma Shape Optimization
- Impurity Control and Boundary Effects
- Fueling

ORMAK, PLT
ORMAK, Alcator, PLT
Doublet IIA, Doublet III, PDX
Alcator, ISX, PDX
PLT, PDX, ORMAK

Minimum-B Mirrors

- Confinement Scaling
- Q-enhancement
- Steady-state Operation

2X-IIB, BB, LITE
2X-IIB, BB, LITE, FRTP
BB, LITE

Toroidally-Linked Mirrors

- Plasma stability
- Microwave heating
- Confinement Scaling

EBT-I
EBT-I
EBT-I, EBT-S

Toroidal Theta Pinch

- Plasma Confinement
- Staged Heating

Scyllac, STP
STP, IHX

Linear Theta Pinch

- End Loss
- High Field Operation

Scylla IV-P, Scylla-IC
Scylla IV-P

Z-Pinch

- Heating
- Profile Optimization

ZT-1, ZT-S
ZT-1, ZT-S

Figure II-1 Critical Problem areas and Key Experiments addressing these problems in the Confinement Systems Program.

C. Recent Achievements

In the past year, important progress has been made toward achieving the plasma conditions and gaining the understanding of observed phenomena necessary for the development of fusion power. These achievements are outlined below, by confinement approach and problem area.

1. Tokamaks

Heating. Major progress in the area of tokamak heating has been achieved with two methods:

1) injection of energetic neutral beams of hydrogen and 2) heating with radio-frequency waves.

Heating by neutral injection was demonstrated at 30 kW and 60 kW power levels during FY 1973

on the Adiabatic Toroidal Compressor (ATC) at PPPL; in August, 1974, neutral beam power of

100 kW was injected and the ion temperature increase continued to scale with injected power;

in August 1975, 250 kW was injected, resulting in an ion temperature increase of up to 300 eV.

In FY 1974 neutral beam injection was demonstrated on the Oak Ridge Tokamak (ORMAK) at ORNL,

at the 200 kW power level. These experiments demonstrated some of the subtle effects of

particle orbits on injection heating. The effects were found by comparison of the results

from experiments in which neutral beams were injected in the same direction as the plasma

current and in the opposite direction (co- and counter-injection). The experimental observation stimulated theoretical analysis leading to improved plasma simulation codes. (The codes are predictive models to aid in designing future experiments.) More recent experiments at higher toroidal magnetic field and higher plasma current have confirmed the predictions of this theoretical work and injecting 250 kW against the current now results in ion heating, in agreement with theory. ORMAK is presently operating with a total injection power capability of 300 kW, about half the ohmic heating power. The result is a trebling of the ion temperature, to 1.5 keV, which is even higher than the electron temperature.

Significant heating with radio-frequency waves was achieved during FY 1974 on the Symmetric Tokamak (ST) at Princeton. Power levels of 100 kW were coupled into the plasma with 90% efficiency and resulted in a doubling of the ion temperature (to 230 eV). A similar system was used on ATC at the 200 kW level with corresponding results.

Transport and Scaling. The area of tokamak physics transport and scaling addresses the physics questions relating larger plasma size, higher magnetic fields and higher currents to plasma temperature, density and confinement time. On ORMAK a modification to the magnet cooling

system has permitted the device to operate at approximately 25 kG (an increase from 18 kG). This higher field has allowed ORMAK to operate at higher current and has provided some improvement in the effectiveness of the injection heating as discussed above. A new power supply recently installed will make possible operation at ~ 30 kG.

In this area, however, the major experimental device is the Princeton Large Torus (PLT) which began operation in December 1975. In early experiments operation at 600 kA for one full second has been achieved at 35 kG, with electron temperatures exceeding 2 keV. A decision to operate at fields up to 50 kG will be made by early 1977. A 4 MW neutral injection system being built at ORNL will be installed during the period Nov. 76 through Mar. 77 and will allow studies of plasma confinement at ion temperatures in excess of 2 keV.

The Alcator at MIT has operated with high toroidal magnetic field (up to 70 kG with a plasma; up to 100 kG without plasma) and large plasma currents (up to 200 kA) in a relatively small plasma cross-section (9 cm radius compared to PLT's 45 cm). The resulting large current densities have produced no deleterious effects on plasma confinement and, in fact, have allowed high density and relatively high temperature operation. Experiments are now being carried out over a wide density range, from less than 10^{13} to greater than 10^{14} particles/cm³; the observed linear dependence of

confinement time on density has been confirmed with experiments on ORMAK, ATC and Pulsator at the Max Planck Institute for Plasma Physics in Garching, Germany. Operation at 75 kG has resulted in a density-confinement time product ($n\tau$) of $10^{13} \text{ cm}^{-3} \text{ sec}$ at a temperature of 1 keV. (For a reactor an $n\tau$ of $3 \times 10^{14} \text{ cm}^{-3} \text{ sec}$ is required at a temperature of 10 keV.)

In the French TFR, plasma currents of 400 kA have been obtained with a toroidal magnetic field of 60 kG, resulting in 3 keV electron temperatures and 1 keV ion temperatures. Neutral injection of 450 kW has increased the ion temperature to between 1.5 and 2.0 keV.

An upgrade of this device to the 600 kA current range is planned for 1976.

In general, confinement time increases with plasma density and in any given tokamak the upper limit on density seems to be given by the total power density, be it from the plasma current, neutral beams, or some combination thereof.

Plasma Shape Optimization. In the area of tokamak plasma shape optimization, experiments are carried out using non-circular plasma shapes in the expectation that vertical elongation of the plasma will result in a reduction of the required toroidal magnetic field strength and will ultimately lead to lower fusion power plant costs. By October 1973 preliminary results on Doublet II at General Atomic Company indicated that a magnetic field one-third that required

for tokamaks with circular plasmas was sufficient to obtain similar plasma parameters in a kidney-shaped "doublet" plasma. This device, now called Doublet IIA, has been modified to allow the production of elliptical and circular plasmas as well as doublets. Initial attempts to center the plasma and stretch it to a two-to-one ellipse have been successful; a comparison of circular and $1\frac{1}{2}$ -to-1 ellipses indicates that an improvement in confinement is achieved. In 1976, effort is concentrated on a systematic study of the doublet configuration. A new power supply will allow operation at 15 kG (cf 7.5 kG at present) by the end of 1976. DIIA is providing data and experience used in the design and planning for Doublet III, now in fabrication and scheduled to operate in early 1978 as a major test of non-circular cross-section physics.

Impurity Control and Boundary Effects. Experiments in the area of impurity control and boundary effects address the problems of the origin of impurities, i.e., the interaction of the plasma with its boundaries, as well as the transport of impurities within the plasma and the detection and control of impurity levels.

In ATC, the evolution of impurities from the walls and limiters has been substantially reduced during the initial plasma buildup phase by evaporating titanium to coat the boundary surfaces before each plasma discharge. The effective Z, or average ion charge (it would be unity for a pure hydrogen plasma), is reduced from two to ≈ 1 .

In Alcator, careful attention to high-vacuum techniques and high-power discharge cleaning seems to provide clean boundary surfaces and result in clean plasma discharges.

There is also the problem of preventing diffusing plasma and neutral particles from interacting with the boundaries during longer plasma discharge times. The magnetic divertor, in which judiciously arranged magnetic field lines near the walls sweep charged particles away into pumping regions, is one solution to the problem of impurities in a "steady state" discharge. The FM-1 demonstrated divertor action effectively in a low-temperature plasma, with 80-90% of the plasma diffusing toward the walls being swept into the divertor region. These experiments confirmed the theoretical basis for the design of PDX, now in fabrication and planned to operate by spring 1978 as a major test of divertor physics.

Fueling. A longer range problem is that of fueling. A steady state reactor requires that the DT fuel be replenished as fast as it is lost through fusion interactions and plasma losses. Prospective fueling methods include gas puffing with neutral beam injection and pellet injection. Very preliminary experiments on ORMAK indicate that pellets do penetrate into the plasma. Further experiments, on ORMAK, PLT, and especially PDX, where recycling of gas from the walls should be greatly reduced, will be very important to the tokamak reactor program.

2. Mirror Systems

The 2X-IIB and BB-IIT experiments at the Lawrence Livermore Laboratory and the LITE experiment at the United Technologies Research Center constitute the major elements of the open-ended mirror-confined fusion plasma research program. The EBT experiment at the Oak Ridge National Laboratory is the major experiment in the toroidal mirror-confined fusion plasma research program.

In July 1975 the 2X-IIB experimental program successfully achieved the near-term goals assigned to it in November 1972 (see WASH-1299): high density ($\epsilon = \omega_{pi}^2 / \omega_{ci}^2 > 100$), $n\tau \approx 10^{11} \text{ cm}^{-3} \text{ sec}$, $T_i \geq 10 \text{ keV}$, and a plasma sustained by neutral beams. Some of the important performance figures are shown below.

Parameter	2X-II Performance October 1972	2X-IIB Performance July 1975
$n(\text{cm}^{-3})$	3×10^{13}	$1 \text{ to } 3 \times 10^{13}$
$T_i(\text{keV})$	6	13
$\tau(\text{ms})$	0.4	5
$n\tau(\text{cm}^{-3} \cdot \text{s})$	10^{10}	7×10^{10}

In October 1975 it was demonstrated in 2X-IIB that the cold-plasma stream used to stabilize the plasma provides a suitable target plasma for build-up of the hot plasma by neutral injection. This demonstration of build-up without the previously used pulsed compression to generate the target provides a solution to a major technical problem for mirrors, i.e., plasma start-up in a steady-state magnetic field.

In February 1976 the density in 2X-IIB was further increased to $1.2 \times 10^{14} \text{ cm}^{-3}$, and the peak value of beta ($\beta = 8\pi nT_i/B^2$) was found to exceed unity, where B is the central vacuum field:

$$\beta_{\text{peak}} = 1.2 \text{ to } 1.6$$

$$\beta_{\text{avg}} = 0.7 \text{ (diamagnetic loop)}.$$

Perhaps more significant is the fact that the 2X-IIB results are quantitatively consistent with the theoretical prediction that warm plasma would suppress the dangerous drift cyclotron loss cone (DCLC) mode. These results are also in agreement with observations from the PR-6 and PR-7 experiments in the Soviet Union. The experiment has confirmed that n_T increases with T_i . Present confinement times are limited by the low electron temperature which is believed to be due to losses on the streaming plasma. Theory suggests that higher electron temperatures and hence larger n_T should result from increased plasma size.

The theoretical stability questions for conventional mirror systems now seem to be well delineated. Three basic modes of instability are important---drift cyclotron loss cone (DCLC), convective loss cone, and Alfvén ion cyclotron (AIC). A good base of theory appears to exist for all of these (studies in the AIC mode behavior are somewhat less developed than the others). Nevertheless, the problems posed by these modes are complex enough that only experiment will determine the precise compatibility with reactor parameters. To test this scaling, a physics experiment substantially larger than the 2X-IIB facility appears necessary. The MX device is projected for this purpose, and is scheduled for operation in 1981.

The BB-IIT experiment is investigating both a means of starting up a mirror machine by neutral beam injection in a steady-state magnet field, and confinement under steady-state conditions. In April 1976 two-sided laser irradiation of 100 μ diameter NH₃ pellets injected into the BB-IIT chamber was achieved using a 300J CO₂ laser. Near term plans are in progress to supplement the 50-amp, 20-keV, 10-msec neutral beam line with three identical units for start-up experiments and two 35-amp, 50-keV, 50-msec beams for plasma sustenance experiments.

The LITE experiment is designed to address the target plasma buildup approach to a steady-state mirror fusion reactor. In September 1975 they demonstrated electrical capture and suspension in hard vacuum of 100 μ LiH target pellets and began two-sided pellet irradiation experiments with a 100J Nd-glass laser. A Heavy Ion Beam probe is being developed to measure the plasma potential. This measurement requires a knowledge of the complex Yin-Yang magnetic field geometry and will produce both spatially and temporally resolved measurements.

The EBT device at ORNL is a non-axially symmetric torus composed of linked magnetic mirrors. EBT has produced a continuously operating stable plasma. The application of modest amounts of microwave power (30 kW) has produced electron temperatures of 300-400 eV. In November 1975 EBT received a very favorable review. The microwave heating power was recently doubled, and experiments are in progress. Experiments designed to test the scaling of the EBT concept with power and size are currently projected for EBT-S and EBT-II.

3. High Density Systems

Feedback experiments began in December 1975, on an 8.4-m (120 $^{\circ}$ arc), derated (reduced magnetic field and temperature), sector of the Scyllac Torus at LASL. Scyllac is designed to investigate

plasma equilibrium and stability in a toroidal theta pinch. Full torus experiments have previously demonstrated plasma production and heating, in the presence of toroidal curvature, and $\ell = 1,0$ equilibrium magnetic fields, to $(T_e + T_i) \approx 1.3$ keV, densities of $\sim 3 \times 10^{16} \text{ cm}^{-3}$, and beta values in the 0.5-0.9 range.

Confinement times of 8-10 μs were achieved in the full torus, being limited by plasma-wall contact. The need for external feedback fields to control this plasma motion has been recognized as an important element to the Scyllac program since its beginning. A high-power feedback system employing optical detection has been developed and installed to overcome this problem. Results with a smooth-bore tube show success in stabilizing plasma motions perpendicular to the major radius, less success in stabilizing plasma motions along the major radius (in or out). The problem in the toroidal plane is attributed to an imperfect initial equilibrium, and steps are being taken to remedy this problem in future Scyllac experiments. These steps include the use of helically shaped, toroidal quartz discharge tubes, and $\ell = 1,2$ equilibria which do not involve the axially-dependent $\ell = 0$ magnetic field component used in earlier experiments. The plasma confinement time in the smooth-bore tube feedback experiments has been extended to the 25-30 μs range.

Scylla IV-P is a 5-meter linear theta pinch capable of producing reactor-grade plasmas ($T_i \sim$ several keV, $n \sim \text{few} \times 10^{16} \text{ cm}^{-3}$, $\beta \sim 1$). Scylla IV-P began operation in January 1976 at LASL, and will be used to study specifically linear physics problems, such as particle end-loss, axial thermal conduction, and high field operation. Initial experiments are concerned with time resolved measurements of the plasma parameters along the length of the device. End-stoppering plans call for the study of material end plugs during 1976 and multiple mirrors in 1977.

ZT-S is an axisymmetric, high beta, toroidal Z-pinch experiment at LASL whose primary mission is to investigate the scaling of plasma confinement time as a function of minor radius (compared to ZT-1) and current density. It is an attractive alternative to the tokamak with MHD stability at $\beta \sim 40\%$ and correspondingly high power density. ZT-S is a modification of ZT-1 to incorporate a larger minor radius and improved electrical circuit. The Z-pinch program received a favorable review in December 1975. The ZT-S results will be reviewed in July 1976 to determine the future course of the Z-pinch program. The larger ZT-P and ZT-II experiments are currently projected as follow-on experiments to ZT-S.

D. Program Structure and Major Milestones

This section discusses the general structure of the three confinement systems programs, as presently conceived for the next five years. The major milestones of the program are presented below; detailed budgets and milestones for each project are given in Volume IV. Budgets consistent with these programmatic aims are summarized in the next section.

1. Tokamaks

The tokamak program is the most highly developed of the Confinement Systems Programs. The anticipated contribution of each of the tokamak devices to each problem area is shown in the flow chart of Figure II-2. The five critical problem areas now being addressed are shown across the bottom of the chart. These problem areas subdivide into problem subareas as follows:

- Transport and Scaling
 - Scaling with size and temperature
 - Scaling with density
- Heating
 - Compression
 - Injection
 - RF
- Configurational Stability
 - Current Distribution
 - Non-Circular Cross-Section
- Boundary Effects
 - Surface Interactions
 - Divertor
- Fueling
 - Gas Blankets
 - Pellet Injection

Major milestones for the Confinement Systems tokamak program have been established as follows:

<u>Program Area</u>	<u>Milestones</u>	<u>Target Date</u>
Heating - Neutral Beams	1. Inject 100 KW into ATC (PPPL)	Aug. 1974 (achieved)
	2. Inject 250 KW into ATC (PPPL)	May 1975 (achieved Aug. 75)
	3. Inject 500 KW into ORMAK (ORNL)	Dec. 1976
	4. Operate 4 MW injection system on PLT (PPPL)	March 1977
	5. Operate 2 MW injection system on ORMAK Upgrade (ORNL)	Oct. 1978
	6. Operate 4 MW injection system on DIII (GA)	July 1979
	7. Operate 30 MW injection system on TFTR (PPPL)	July 1981
Heating - RF	1. Test 200 KW of RF in ATC (PPPL)	May 1975 (achieved)
	2. Decide whether to proceed with fabrication on 2.5 MW RF supply for PLT (PPPL)	Sept. 1976
	3. Test 2.5 MW of RF on PLT (PPPL)	July 1979
Transport and Scaling	1. Begin operation of ORMAK at higher field (~ 25 kG) with higher installed neutral beam power (~ 200 KW) (ORNL)	Dec. 1974 (achieved)
	2. Begin operation of PLT (PPPL)	Dec. 1975 (achieved)
	3. Evaluate operation of Alcator at high field (~ 90 kG) (MIT)	Jan. 1977
	4. Begin operation of ORMAK at 33 kG with higher plasma current (~ 200 kA) (ORNL)	July 1976
	5. Evaluate plasma results from PLT (PPPL)	Sept. 1976
	6. Evaluate 33 kG operation of ORMAK (ORNL)	Feb. 1977
	7. Evaluate 4 MW heating experiments in PLT (PPPL)	Sept. 1977

<u>Problem Area</u>	<u>Milestones</u>	<u>Target Date</u>
Plasma Shape Optimization	1. Evaluate plasma shape control in Doublet IIA (GA) 2. Evaluate results from Doublet IIA (GA) 3. Evaluate current distribution in PLT (PPPL) 4. Operate Doublet III (GA) 5. Evaluate Doublet III results (GA) 6. Evaluate stability in D-shaped plasma in PDX	July 1975 (achieved, Aug. 75) July 1976 Sept. 1976 Feb. 1978 Dec. 1978 April 1979
Impurity Control and Boundary Effects	1. Decide whether to proceed with ISX (ORNL) 2. Evaluate Impurity Effects in PLT (PPPL) 3. Operate PDX (PPPL) 4. Evaluate impurity control in ohmically heated PDX (PPPL)	July 1975 (achieved) Sept. 1976 April 1978 Dec. 1978
Fueling	1. Test first generation pellet fueling device on ORMAK 2. Test 200 μ m pellet injector from U. of Illinois on ORMAK 3. Test 3 x 10 ⁵ cm/sec pellet injector on PLT 4. Operate pellet injector on PDX	Sept. 1975 (achieved) Nov. 1976 June 1978 June 1979

2. Mirror Systems

The outstanding success of the recent experiments in 2XIIB, which have investigated start-up, stabilization, heating, and fueling of mirror systems by neutral injection into a target

plasma, have increased the fundamental understanding of mirror confinement physics. The mirror program underwent three intensive reviews in the first half of 1976. The Mirror Senior Review Panel reviewed the program in March 1976 (ERDA 76-74) and recommended an expanded national program in mirror research with emphasis on Q-enhancement experiments, and construction of an MX-scale device for confinement scaling studies. The Fusion Power Coordinating Committee (FPCC) reviewed the program in April 1976, and issued the following position statement:

- "1) The national magnetic mirror program should be strengthened. The program should build vigorously on the positive results of the past year, to enhance and accelerate progress towards the national goal of producing a practical pure fusion power reactor.
- "2) A magnetic mirror device with the general goals of the proposed MX should be authorized as a line item in the FY 1978 budget, with an initial operating date of 1981. A review panel should be convened to consider the MX proposal and define, with LLL participation, the appropriate device, considering both technical objectives and cost, required to clarify the physics basis for mirror fusion reactor designs, as the next logical step in research on this confinement method. The recommended device should have sufficient flexibility to allow Q enhancement experiments.

- "3) A program plan for increasing Q in magnetic mirrors should be prepared. This plan should include testing, with high priority, under leadership of LLL, methods for increasing Q in existing devices or in new devices of modest size, coupled with substantially increased theoretical work."

A technical review panel was convened in May 1976, at LLL to conduct an engineering review of the MX proposal, address general questions of Q-enhancement, and define the nature of the next major step in the mirror program. The project data sheets which are given in Volume IV for the mirror program represent an expanded funding level over that supported under the previous "Open Systems" program, and reflect an increased national involvement. Individual milestones for existing experiments, 2X, BB, and LITE in particular, will be subject to further changes as the national mirror program plan evolves with added emphasis on Q-enhancement studies.

Major milestones for the magnetic mirror program have been established as follows:

<u>Problem Area</u>	<u>Milestones</u>	<u>Target Date</u>
<u>Minimum-B Mirrors</u>		
Confinement Scaling	1. DMFE decision on MX proposal	July 1976
	2. Extend $n\tau$ (T_i) scaling from 13 keV to 20 keV in 2XB	Oct. 1976
	3. Increase radial dimension of plasma from $R/\rho_i \sim 2-4$ to 5-10 in 2XB	March 1977
	4. Begin plasma experiments in MX	Sept. 1981

<u>Minimum-B Mirrors (continued)</u>	<u>Milestones</u>	<u>Target Date</u>
Q-enhancement	1. Develop DMFE program plan for Q-enhancement investigations	Oct. 1976
Steady-State	1. Preliminary evaluation of quasi-steady-state (≥ 0.5 sec) operation in BB mirror system	March 1978
	2. Begin plasma stabilization investigations in high density, injection-sustained LITE plasma	June 1978

Toroidally-Linked Mirror

Plasma stability, micro-wave heating and confinement scaling	1. Evaluate results on EBT-I	April 1977
	2. Begin plasma experiments in EBT-S	August 1977
	3. DMFE decision point for EBT-II	Sept. 1977

3. High Density Systems

August 1977 is the DMFE decision point on whether to proceed further with the toroidal theta pinch program at LASL. This decision will involve a review of results on plasma confinement and staged heating experiments on Scyllac and STP, and an evaluation of future prospects for this high density system. If an expanded effort for the toroidal theta pinch program is approved, the lead experiment at LASL will be Staged Scyllac, which is envisioned as the proof-of-principle experiment for the toroidal theta pinch

concept. The toroidal Z-pinch and linear theta pinch experiments would serve in the capacity of back-up concepts, and would be funded accordingly. If the toroidal theta pinch program should be terminated, the program emphasis at Los Alamos would shift to the Z-pinch line of experiments, with the linear theta pinch approach continuing to serve as a back-up.

The project data sheets which are given in Volume IV for high density systems reflect scenario 1 (i.e., the toroidal theta pinch-Staged Scyllac - line of research) is the lead program at LASL. Detailed project data sheets and program plans have also been prepared for scenario 2 (Z-pinch is the lead program and the linear theta pinch is the back-up program); however, project data sheets for this alternate program scenario are not given in Volume IV.

<u>Problem Area</u>	<u>Milestone</u>	<u>Target Date</u>
<u>Toroidal Theta Pinch</u>		
Plasma confinement	1. Evaluation of feedback stabilization in Scyllac and initial wall stabilization in Staged Theta Pinch	July 1977
Staged Heating	1. Evaluate staging experiments in Staged Theta Pinch	

<u>Problem Area</u>	<u>Milestone</u>	<u>Target Date</u>
<u>Linear Theta Pinches</u>		
End loss	1. Evaluate end-stoppering experiments in Scylla IV-P	Jan. 1978
High field operation	1. Begin high field operation in Scylla IV-P	Jan. 1978
<u>Z-Pinches</u>		
Heating and profile optimization	1. Review of ZT-S results and ZT-P proposal	Sept. 1976

4. Future Experiments

a. Tokamaks

Two experiments not discussed above are expected to be proposed in FY 1977-78. At Princeton Plasma Physics Laboratory a small toroidal device is under consideration. It would be specially designed to provide a controlled and localized ripple in the toroidal field which would be large enough (70-80 kG) to provide a high density ($3\text{-}6 \times 10^{14} \text{cm}^{-3}$) plasma. This device would then be used to test vertical neutral beam injection, or ripple injection, a concept which offers the possibility

of beam penetration and heating at lower beam energy and with less access than required for present-day tangential injection systems.

At General Atomic a small superconducting tokamak is under consideration. Its focus would be rf heating and it would also test the possibility of driving a steady state plasma current by use of rf power.

b. Mirror Systems

The major experiments projected in the mirror program are MX at LLL, MRTX at UTRC and EBT-II at ORNL. The major objective of the MX experiment is to provide data on open systems confinement scaling laws in an $n\tau$ range near $10^{12}\text{cm}^{-3}\text{sec}$. A secondary objective of MX, and the primary objective of MRTX, is to extend the operating regime for mirrors into the multisecond regime to reach an equilibrium state for wall-reflux neutrals. The EBT-II device is intended to provide heating and confinement information for toroidally linked mirrors in a significantly larger facility than EBT-I.

c. High Density Systems

Under the toroidal theta pinch scenario, the primary experiment planned at LASL is Staged Scyllac, which involves an $\sim \$10\text{M}$ modification of the existing Scyllac bank. For the Z-pinch program, the ZT-P and ZT-II experiments are projected.

If end-stoppering research is successful on Scylla IV-P, a Long Linear Experiment (LLX) is planned, which will extend the confinement physics into the $n\tau \sim 10^{13}\text{cm}^{-3}\text{sec}$ range.

E. Budget Summary

The budgets necessary to achieve the objectives discussed in Section D are displayed in Figure II-3.

CONFINEMENT SYSTEMS BUDGETS

	Dollars in Thousands								
	Fiscal Years								
A. Operating	1976	1976T	1977	1978	1979	1980	1981	1982	Total 78-82
<u>Confinement Systems</u>	61,900	19,300	79,600	110,000	125,000	140,000	140,000	150,000	665,000
<u>Tokamaks</u>	43,200	13,750	57,400	70,000	75,000	80,000	80,000	80,000	385,000
<u>PPPL</u>									
PLT Normal Op.	6,330	1,900	8,100	11,400	11,000	11,000	11,000	11,000	55,400
PLT Fab.	1,880	0	0	0	0	0	0	0	0
PLT NB	2,550	300	250	0	1,500	3,500	3,000	0	8,000
PLT RF	0	0	2,300	3,500	2,500	0	0	0	6,000
PDX Normal Op.	2,470	1,350	7,200	10,000	10,000	10,000	10,000	11,000	51,900
PDX Fab.	6,770	2,700	5,100	2,200	0	0	0	0	2,200
PDX NB	0	0	650	2,200	0	5,000	2,000	0	9,200
PDX Upgrade	0	0	0	0	0	3,000	2,000	0	5,000
ATC	1,600	0	0	0	0	0	0	0	0
<u>ORNL</u>									
ORMAK Normal Op.	3,500	850	2,700	0	0	0	0	0	0
ORMAK Fab.	500	0	0	0	0	0	0	0	0
ORMAK Upgrade Normal Op.	0	0	1,500	4,500	7,000	7,000	7,000	7,000	32,500
ORMAK Upgrade Fab.	200	250	3,300	3,700	0	0	0	0	3,700
ORMAK Upgrade NB	0	0	0	1,000	2,000	0	0	0	3,000
ORMAK Upgrade RF	0	0	0	0	0	0	4,000	4,000	8,000
ISX Normal Op.	300	100	2,500	2,700	2,700	3,000	3,000	3,000	14,400
ISX Fab.	1,500	400	600	0	0	0	0	0	0
ISX RF	0	0	0	0	300	2,000	0	0	2,300
PLT NB Lines	900	650	500	0	0	0	0	0	0

Figure II-3

Dollars in Thousands

Fiscal Years

	<u>1976</u>	<u>1976T</u>	<u>1977</u>	<u>1978</u>	<u>1979</u>	<u>1980</u>	<u>1981</u>	<u>1982</u>	<u>Total 78-82</u>
<u>GA</u>									
DIII Normal Op.	1,200	500	4,200	8,640	10,000	10,000	10,000	10,000	48,640
DIII Fab.	8,700	3,500	11,300	2,560	0	0	0	0	2,560
DIII NB	0	0	200	6,000	9,000	4,000	6,000	6,000	31,000
DIII Upgrade	0	0	0	0	3,000	7,000	7,000	0	17,000
DIIA Normal Op.	2,600	600	3,300	3,700	2,500	0	0	0	6,200
DIIA Fab.	400	0	0	0	0	0	0	0	0
ISX	100	50	500	500	500	500	500	500	2,500
<u>MIT</u>									
Alcator A Normal Op.	1,500	350	1,350	1,000	0	0	0	0	1,000
Alcator C Normal Op.	0	500	350	1,500	3,000	3,000	3,000	3,000	13,500
Alcator C Fab.	200	250	1,000	1,500	0	0	0	0	1,500
Alcator C Power Supply ...	0	0	0	2,500	0	0	0	0	2,500
Alcator C RF	0	0	0	0	1,000	1,000	0	0	2,000
Alcator C Upgrade	0	0	0	0	0	0	1,500	9,500	11,000
<u>Other</u>									
Normal Op.	0	0	0	0	2,000	6,000	7,000	10,000	25,000
Fab.	0	0	0	0	7,000	4,000	3,000	5,000	19,000
<u>Mirror Systems</u>									
2XIIB & 2XB	10,900	3,560	14,045	28,900	36,400	41,100	36,900	40,700	184,000
2XC	5,700	1,560	5,100	6,100	7,800	7,900	3,500	3,500	28,800
MX	0	0	600	1,600	0	0	0	0	1,600
BBIIT	0	150	1,100	3,100	6,800	6,400	11,300	15,000	42,600
BB-MB	2,150	500	1,800	1,800	0	0	0	0	1,800
Advanced Concepts	0	475	1,400	2,300	4,700	5,200	4,500	5,200	21,900
LITE	0	0	100	1,500	2,000	2,000	2,000	2,000	9,000
MRTX	1,650	425	1,700	2,100	1,900	500	0	0	4,500
QX	0	0	0	1,000	1,100	5,200	2,600	3,000	12,900
EBT-I, EBT-S	0	0	0	2,600	3,600	2,200	3,500	5,000	16,900
EBT-II	1,400	350	1,800	2,700	3,000	1,500	500	0	7,700
FRTP	0	100	200	2,900	5,000	9,000	8,500	7,000	32,400
	0	0	245	1,200	1,000	1,200	500	0	3,900

Figure II-3 (continued)

Dollars in Thousands									
Fiscal Years									
	1976	1976T	1977	1978	1979	1980	1981	1982	Total 78-82
<u>High Density Systems</u>	7,800	1,990	8,155	11,100	13,600	18,900	23,100	29,300	96,000
Scyllac	3,750	950	1,205	900	0	0	0	0	900
Staged Scyllac	0	0	80	5,000	7,000	8,000	7,500	5,500	33,000
Large Staged Scyllac	0	0	0	400	1,200	1,200	4,100	6,800	13,700
Staged Theta Pinch	1,400	300	1,100	530	0	0	0	0	530
ZT-S	850	300	530	300	0	0	0	0	300
ZT-P	0	0	3,510	2,140	2,300	2,500	1,000	0	7,940
ZT-II	0	0	0	0	800	4,500	7,500	11,300	24,100
Scylla IV-P	1,650	415	1,670	1,700	2,200	2,500	2,500	3,200	12,100
LLX	0	0	0	100	100	200	500	2,500	3,400
Conceptual Studies	150	25	60	30	0	0	0	0	30
B. Equipment									
<u>Confinement Systems</u>	7,720	2,450	8,200	15,160	17,400	17,260	18,490	20,350	88,660
Tokamaks	4,458	1,400	5,800	8,550	9,900	9,700	9,800	9,800	47,750
Mirror Systems	2,215	790	1,435	7,020	7,400	5,060	5,590	6,420	31,490
High Density Systems	1,047	260	965	1,190	1,600	2,500	3,100	4,130	12,520
C. Line Item Construction									
Dollars in Millions									
<u>Confinement Systems</u>	0	0	0	31.0	60.4	25.7	10.0	73.6	200.7
Tokamaks	0	0	0	0	0	0	0	0	0
Mirror Systems	0	0	0	31.0	60.4	25.7	0	0	117.1
MX	0	0	0	31.0	48.0	21.0	0	0	100.0
MRTX	0	0	0	0	12.4	4.7	0	0	17.1
High Density Systems	0	0	0	0	0	0	10.0	73.6	83.6
Large Staged Scyllac	0	0	0	0	0	0	0	39.6	39.6
Scyllac Fusion Test									
Reactor	0	0	0	0	0	0	0	0	0
Long Linear Expt	0	0	0	0	0	0	0	19.0	19.0
ZT-II	0	0	0	0	0	0	10.0	15.0	25.0

Figure II-3 (continued)

III. TECHNICAL PROJECTS OFFICE

A. Introduction

The Technical Projects Office (TPO) is responsible within MFE for the management of the design and construction of large complex line item fusion facilities, including development programs in direct support of the projects. During FY 1976 TPO has provided program management of the Tokamak Fusion Test Reactor (TFTR) at Princeton Plasma Physics Laboratory. PPPL is the prime contractor for the design and fabrication of the TFTR device and the associated hardware, much of which will be engineered and fabricated in industry. The ERDA Princeton Area Office is responsible for administration of the project, including prime contracting for the conventional facilities. PPPL will operate the experiment and facilities when construction is complete. Within MFE, the Confinement Systems Subprogram will manage the experimental program after completion of construction.

In addition, the Technical Projects Office manages the design and construction of facilities capable of producing intense sources of high energy neutrons required to determine the effects of high energy neutrons on reactor materials. The Rotating Target Neutron Source (RTNS) embodies known technology and is scheduled for completion in FY 1978. The Intense Neutron Source (INS), authorized for funding in FY 1977, is scheduled for completion in FY 1981.

Conceptual design studies performed in the Development and Technology subprogram will identify specific goals and design criteria for future large fusion facilities. Responsibility for the final design and construction will be transferred to the Technical Projects Office.

B. Tokamak Fusion Test Reactor

1. Introduction

The Tokamak Fusion Test Reactor (TFTR) will be the nation's first magnetic confinement fusion device to experimentally demonstrate the release of fusion energy from the deuterium-tritium reaction under conditions projected for future experimental power reactors. TFTR will represent an intermediate step between present, relatively small zero-power physics experiments and future experimental reactors planned for the mid-1980's. The TFTR will be located at the Princeton Plasma Physics Laboratory (PPPL) near Princeton, New Jersey. The construction project should be completed in mid-1981 at a total cost of \$228M, including escalation.

2. Objectives

The TFTR has major objectives in both physics and engineering. The principal objectives are:

- a. To demonstrate fusion energy production from the burning of deuterium and tritium (DT) in a magnetically confined toroidal plasma system.

b. To build a neutral beam heated tokamak in which hydrogen, deuterium and DT plasma can be inserted in order to:

(1) Study the physics of large tokamaks, and

(2) Verify advanced engineering concepts for DT tokamak systems,

c. To experimentally demonstrate that sufficient physics and engineering understanding of large fusion systems exists in advance of construction of an Experimental Power Reactor.

The TFTR will serve as an intermediate step to bridge the gap between current, relatively small, hydrogen plasma confinement experiments and the first Experimental Power Reactor. The unique features required are its DT burning capability, its size which permits physics experiments in the EPR range of interest and some of its engineering features, not heretofore tested. The experience to be gained in design, construction and operation, and the information to be gathered in physics and engineering will provide a sound foundation for EPR design and construction.

The specific objectives of the TFTR project are:

- Attain reasonable pure hydrogenic plasma conditions at 5-10 keV temperature, approximately 10^{14} cm^{-3} density, and provide stable confinement with $n\tau_E$ equal to or greater than $10^{13} \text{ cm}^{-3} \text{ sec}$.

- Provide a neutral beam injection system capable of injecting into the plasma 20 MW of 120 keV D^0 beam, for at least 0.5 sec.
- Provide a toroidal magnetic field of about 5 tesla (on vacuum chamber axis), for at least 3-sec flat-top time, with a 5-min. repetition rate.
- Develop plasma handling techniques and provide hardware capable of initiation, control (including feedback control and major radius compression) and dissipation of tokamak discharges up to 2.5 MA.
- Provide a vacuum chamber of adequate size (2.7 m major radius and 1.1 m minor radius), equipped for high-power discharge cleaning and capable of achieving base pressures below 5×10^{-8} Torr.
- Provide capability for routine pulsed operation with H-H; D-D; $D-He^3$; or DT plasmas, with safe and reliable gas handling and support systems.

3. Principal Design Features

The principal design features of TFTR are:

Size

- 2.7 m major radius

Plasma

- 2.5 MA maximum plasma current
- 1.7 meter diameter
- Target plasma conditions $n\tau \sim 10^{13}$; $T_i \sim 5$ keV

Neutral Beam Injection

- 120-150 keV

Magnets

- Water-cooled copper
- 50 kG centerline field
- Provision for adiabatic compression ($c = 1.5$)

Power Supply

- 4500 MJ, 660 MW pulsed
- AC motor/generator/flywheels

Special Features

- Tritium supply and containment systems
- Shielded magnets and auxiliary systems
- Remote handling capability
- Neutron and plasma diagnostics

Energy Release

- 1-10 MJ with D-T

4. Project Milestones

Major milestones for the TFTR project are:

- | | |
|---|-----------|
| ● Order long lead material (Toroidal Field coils) | Dec. 1976 |
| ● Order Motor-Generator-Flywheel System | Dec. 1976 |
| ● Start Site Construction | Feb. 1977 |

● Complete Tokamak System Final Design Review	Aug 1977
● Initiate Fabrication of Vacuum Vessel	May 1978
● Initiate Fabrication of Toroidal Field Coils	Oct 1978
● Order Neutral Beam Systems Production Unit	Apr 1979
● Delivery of first MG set	Oct 1979
● Complete TFTR Complex Construction	Jan 1980
● Start Final Assembly of Tokamak	May 1980
● Initiate Testing of Neutral Beam Line #1	Jul 1980
● Complete Site Construction	Nov 1980
● Hydrogen Plasma Operation	Jun 1981

5. Projected Budgets (\$M)

	1976	1976A	1977	1978	1979	1980	1981	1982	FY78-82 Total
Construction: (TEC \$228.0)	15.0	5.5	80.0	94.4	32.7	0	0	0	127.1
<u>Operating (Total)</u>	<u>0.4</u>	<u>0.8</u>	<u>10.0</u>	<u>15.3</u>	<u>10.3</u>	<u>20.0</u>	<u>23.0</u>	<u>25.0</u>	<u>93.6</u>
Component Dev.	0.4	0.8	9.5	12.3	3.0	2.6	2.3	0	20.2
Exp. Research	0	0	0.25	1.6	2.8	5.6	6.2	10.0	26.2
Facilities Oper.	0	0	0.25	1.4	4.5	11.8	14.5	15.0	47.2
<u>Equipment</u>	0.15	0.05	1.0	2.0	2.7	2.9	1.3	0	8.9

C. Rotating Target Neutron Source

1. Introduction

The Rotating Target Neutron Source (RTNS-II) will be the first high-energy, high-intensity neutron irradiation facility dedicated to the fusion reactor materials program. The RTNS-II will provide the neutron sources and support facilities required to provide the "pure" 14 Mev neutron energy component necessary as a base line for displacement and transmutation studies. This facility will be located at the Lawrence Livermore Laboratory (LLL), Livermore, California. LLL is the prime contractor for the design and fabrication of the facilities. LLL will operate the facility when completed in 1978, at a total construction cost of \$5M, including escalation. The ERDA San Francisco Operations Office is responsible for administration of the project, including cost, schedule and technical monitoring.

2. Objectives

This 14 MeV source is intended to provide:

- high energy damage information at low fluences required for verification of theories of fission data extrapolation;
- surface and defect data for comparison with high energy spectra such as those arising from the Be(D,n) and Li(D,n) stripping reactions, which have tentatively been identified as possible reactions upon which to base a higher intensity, larger volume neutron source;
- cross-section measurement data;
- synergistic effects on materials due to the interaction of neutron damage with other plasma radiation; and
- comparison with ion simulation.

The design requirement and overall performance specification for RTNS-II is for two source strengths of 4×10^{13} n/sec. The source is based on the D-T reaction produced by ~~impinging~~ an accelerated deuterium beam on a solid, rotating, titanium tritide target.

3. Principal Design Features

Number of Sources	2
Beam Current (400 kev)	150 MA
Spot Size	1 cm
Source Strength	4×10^{13} n/sec
Maximum Flux	1×10^{13} n/cm ² -sec
Target Size	46 cm
Target Speed	5000 rpm
Target Lifetime	100 hours
Test Volume	1 cc

4. Major Project Milestones

Completion of Preliminary Proposal	May 1976
Start Excavation	Sep 1976
Initial operation of accelerator prototype	Mar 1977

Complete site construction activities	Aug 1977
Complete final target design	Sep 1977
Operate first source, project completion	Feb 1978

5. Projected Budgets

The Technical Projects Office budget provides operating funds for the RTNS through FY 78, the year of project completion. Funding for subsequent years is provided in the Development and Technology budget.

	1976	1976A	1977	Fiscal Years		1980	1981	1982	Total 78-82
				<u>Millions</u>					
				1978	1979				
Construction: (TEC \$5.)M	2.5	0	2.5	0	0	0	0	0	0
Operating	0.0*	0.0*	0.0*	1.2	0	0	0	0	1.2
Equipment	0.0*	0.0*	0.0*	0.11	0	0	0	0	0.11

D. Intense Neutron Source

1. Introduction

The Intense Neutron Source (INS) is the second high-energy, high-intensity neutron irradiation facility dedicated to the MFE reactor materials program, the first being RTNS-II. The INS will provide higher 14-MeV neutron source intensities and a larger experimental volume than its predecessor, the RTNS-II.

This facility will be used to study the behavior of candidate materials for fusion devices (such as EPR-I)

under radiation-damage conditions similar to that anticipated in large fusion reactors. The facility will provide prototype neutron flux levels and will have expanded volumetric capability to investigate microstructures, to perform initial screening for mechanical properties of candidate materials, and to examine blanket moderated spectrum effects. This facility will be located at the Los Alamos Scientific Laboratory (LASL), Los Alamos, New Mexico. LASL is the prime contractor for the design and fabrication of the facilities. LASL will operate the facility when completed in 1981, at a total construction cost of \$25.4M, including escalation. The Los Alamos Area Office is responsible for administration of the project, including cost, schedule and technical monitoring.

2. Objectives

This 14 MeV source is intended to provide:

- high energy damage information at high fluences required for verification of theories of fission data extrapolation
- microstructural and mechanical property data for comparison with high energy spectra such as those arising from the Be(D,n) and Li(D,n) stripping reactions, which have tentatively been identified as possible reactions upon which to base a higher intensity, larger volume neutron source;
- neutronic studies in tritium breeding blankets;
- mock fusion reactor first wall life tests;

- neutron cross-section measurement data; and
- data on tritium behavior and handling.

The design requirement and overall performance specification for INS is for two source strengths of 1×10^{15} n/sec. This source is based on the DT reaction produced by accelerating a tritium beam to react with a supersonic deuterium gas target.

3. Principal Design Features

Number of Sources	2
Beam Current (270 keV)	1.1A
Jet Target Volume	1 cc
Source Strength	1×10^{15} n/sec
Maximum Flux	1.2×10^{14} n/cm ² sec
Test Volume	3 cc

4. Major Project Milestones

Title I begins	Oct. 1976
Title II begin	July 1977
Title III and construction begins	Feb. 1978

Construction complete

Apr 1980

Facility operational

Jan 1981

5. Projected Budgets

The Technical Projects Office budget provides operating funds for the INS through FY 81, the year of project completion. Funding for subsequent years is provided in the Development and Technology budget.

	<u>Fiscal Years</u> <u>Millions</u>								Total
	1976	1976A	1977	1978	1979	1980	1981	1982	78-82
Construction: (TEC \$25.4M)	.100	0	14.4	10.9	0	0	0	0	10.9
Operating	0*	0*	0*	1.5	1.7	2.0	2.0	0	7.2
Equipment	0*	0*	0*	0.19	0.8	0.1	0.1	0	1.19

* Carried under D&T funding budget for FY 76-77

IV. DEVELOPMENT AND TECHNOLOGY

A. Introduction

In 1973, the Development and Technology program (D&T) was created within the Division of Magnetic Fusion Energy (then the DCTR) to provide near term engineering/subsystems support to existing and proposed experiments and, in the longer term, to provide development of the technology which will be necessary for fusion energy to become commercial reality. These both remain as the fundamental objectives of the D&T program; only the scope of the program objectives has expanded as the DMFE enters into the Fusion Reactor Engineering phase of Fusion Power RD&D.

Development and Technology program activities presently are organized in five technical problem areas:

- Magnetic Systems - This activity sponsors research and development of large superconducting magnet systems needed for Fusion Reactor Engineering experiments within the next ten years. Examples include toroidal field magnets and ohmic heating coils for tokamaks, yin yang coils for mirrors, and superconducting inductive energy stores for theta pinches. These systems will be necessary for both plasma confinement and energy storage.

- Plasma Engineering - This activity is directed principally at the development of efficient plasma heating systems (neutral particle beams, radiofrequency waves, and electromagnetic plasma implosion systems) that are essential for all approaches to commercial fusion energy by magnetic confinement. Additional responsibilities include direct energy conversion, vacuum component development, and plasma maintenance and control systems.
- Fusion Reactor Materials - The purpose of this long lead-time activity is to develop the high performance reactor materials required for the economical generation of energy from the fusion process. The principal focus is on materials that will be placed within the first ten centimeters or so of the plasma where the fusion radiation environment imposes the most difficult materials requirements. Other areas of effort include development of those materials to a fusion reactor design (e.g., both hot and cryogenic insulators, special structural materials).
- Fusion Systems Engineering - This activity focuses principally on the next generation and longer term fusion power reactor designs. Specifically, a major activity is the support of necessary reactor design efforts to enable the DMFE to assess the desirability of alternative fusion prototype experimental power reactor configurations presently planned to operate in 1985 or 1986. Other Fusion Systems Engineering activities include systems studies of fusion applications and economics, blanket and shield engineering, tritium processing and control, plasma

systems, and plant systems design and test. A major near-term activity will be the development and prototyping of engineered tritium processing and control systems that will be required for tritium burning experimental fusion reactors.

- Environment and Safety - The purpose of this activity is to pursue technical programs which will assure that fusion power reactors will operate with no potential for hazard either to the environment or to plant personnel and nearby populations. At this time, Environment and Safety efforts focus on environmental impact analysis, facility safety analysis, and reactor safety research.

Development and Technology activities, introduced above and discussed in detail in the following sections, will grow and evolve to fit the requirements of an integrated Magnetic Fusion Energy research and development program. A key element in the structuring of these activities is our current perception and anticipation of the requirements for engineering development and technology for future fusion reactors. Thus the following plan, which is designed to pursue the next five years in the Logic III long range projection, represents our best judgement of what must be accomplished during the next few years. As technical progress in physics and engineering occurs, our plans will be modified as needed.

In preparing the current portion of the Development and Technology five-year plan, the following assumptions were made with regard to overall Logic III milestones.

- Tokamak confinement continues to be the main approach, but mirrors and other advanced systems (principally high beta theta-pinch) will continue as alternate confinement concepts.
- Mirrors are the most attractive alternate confinement concept at this time. MX is planned to operate in 1981.
- The next major facility, a Tokamak Prototype Experimental Power Reactor/Ignition Test Reactor (PEPR/ITR) is planned for operation in 1985/86 with Title I funding to begin in 1979. This reactor is also referred to as the TNS.
- Development and Technology activities must maintain pace with the PEPR/ITR, but also must meet the requirements of nearer term facilities (Doublet-III, PLT, PDX, ORMAK-Upgrade, MX, and TFTR).

Table IV-1 presents the budget summary of the Development and Technology program through FY 1982.

Table IV-1

Development and Technology
Budget Summary

	Fiscal Year (Millions)								FY 78-82 Total
	FY 1976	FY 1976T	FY 1977	FY 1978	FY 1979	FY 1980	FY 1981	FY 1982	
MAGNETIC SYSTEMS	\$ 7.35	\$ 1.85	\$17.75	\$19.0	\$25.0	\$28.0	\$32.1	\$37.2	\$141.3
PLASMA ENGINEERING	10.11	3.71	19.70	21.0	25.0	26.0	29.8	34.5	136.3
FUSION REACTOR MATERIALS	6.87	1.75	9.35	16.0	20.0	23.0	26.3	30.5	115.8
FUSION SYSTEMS ENGINEERING	8.67	2.01	10.3	18.0	23.0	30.0	34.4	39.9	145.3
ENVIRONMENT & SAFETY	.45	.11	.95	1.0	2.0	3.0	3.4	3.9	13.3
TOTAL OPERATING	\$33.45	\$ 9.43	\$58.05	\$75.0	\$95.0	\$110.0	\$126.0	\$146.0	\$552.0
TOTAL EQUIPMENT	\$ 5.18	\$ 1.0	\$ 5.66	\$ 8.50	\$15.3	\$ 16.0	\$ 19.2	\$ 20.0	\$ 79.0

The following sections describe the major activities of the Development and Technology program in some detail. Each section presents the objectives and scope, technical/management approach, notable recent achievements, and the near term major milestones and funding requirements for the D&T program activities briefly described above.

B. Magnetic Systems

As magnetic fusion experiments approach reactor size, energy and cost considerations force a departure from conventional copper magnets and power supplies. Superconductors offer the potential for meeting all necessary requirements, but the materials, magnets, and energy storage devices must be substantially improved and enlarged for even a Prototype Experimental Power Reactor.

The purpose of Magnetic Systems is the engineering design and component development of large superconducting magnet systems for future tokamak and mirror experiments, to develop superconducting ohmic heating coils and power supplies, and to develop fast-discharge energy storage systems for pulsed high beta concepts. Large (approximately three meter diameter) coils are being developed for assembly into a Compact Torus, and high field superconducting materials developed for mirror experiments. These major activities are supported by numerous efforts in the base technologies of magnet design, cryogenics, materials development and systems analysis. In addition both magnetic and homopolar energy storage devices are being developed for high beta plasma experiments and tokamak ohmic heating systems.

The management approach is to identify a magnet performance requirement for current or future projects authorized by DMFE management. A review of the present technology is conducted to arrive at any assessment of what developments are necessary, and proposals encouraged from national laboratories, universities and industries. The detailed development schedule, cost and program integration are

planned with field participation and funding provided for implementation. The evaluation of development progress is accomplished through visits, reports and technical review meetings.

Management is striving to engage and to develop industry in appropriate areas of MFE development, and to transfer basic manufacturing technology from the national laboratories to the industry. This includes not only hardware fabrication, but design and development of reactor components and systems as well. As a result, the NbTi and Nb₃Sn superconductors are being developed and produced in industry, as are energy storage magnets. Recently, the conceptual design of EPR-I magnets was contracted to three industrial firms from which large prototype coils can be constructed. Table IV-2 summarizes the current and projected funding requirements for Magnetic Systems.

Table IV-2

Fiscal Years
Millions

	1976	1976A	1977	1978	1979	1980	1981	1982	FY 78-82 Total
Magnetics									
Operating	5.20	1.40	15.45	16.40	21.00	23.00	25.10	29.20	114.70
Equipment	1.01	0.27	1.60	2.20	4.35	4.90	6.95	7.95	26.35
Energy Storage									
Operating	2.20	0.45	2.30	2.60	4.00	5.00	7.00	8.00	26.60
Equipment	0.24	0.05	0.25	0.50	0.50	0.70	0.70	1.00	3.40
Total Magnetic Systems									
Operating	7.40	1.85	17.75	19.00	25.00	28.00	32.10	37.20	141.30
Equipment	1.25	0.32	1.85	2.70	4.85	5.60	7.65	8.95	29.75

1. Magnetics

Advancing the size, reliability and performance of present day laboratory magnets involves the development and integration of many interdisciplinary tasks. Engineers, physicists, and metallurgists must all combine talents to make such a hybrid technology satisfy the fusion magnet requirements of 8-16 T fields with up to 20 meter diameters in a hostile pulsed-field and radiation environment.

Objectives and Scope

The objective of the magnetics activity is to develop the large, reliable superconducting magnets and magnet systems that will be necessary to confine plasmas for the tokamak, mirror, and other magnetic fusion concepts. Tokamak reactor studies project the need for "D" shaped niobium-titanium and possibly high field niobium-tin superconducting magnets with inside dimensions that may be as large as 20 meters, which, when arranged in toroidal geometry, will produce a central field of 4 to 6 Tesla and a peak field between 8 and 12 Tesla. The mirror concept utilizes a Yin-Yang magnet enclosing a sphere of 8 to 10 meters in diameter; the superconducting windings would be niobium-tin and produce a vacuum central field of about 5 Tesla, a field in the mirror region of 10 Tesla and a peak field of about 12 Tesla.

Technical Approach

In order to develop such large superconducting tokamak magnets, the Large Coil Project was initiated at ORNL. Three industries are now preparing conceptual designs for the EPR magnets and recommendations for a subsize prototype to demonstrate the technology. Six prototype magnets will be constructed to the same performance specification by industry, ORNL, and through an IEA collaboration and assembled into a Compact Torus. By having multiple contractors a variety of magnet designs can be tested in

realistic toroidal array. All of the coils in the test configuration will be EPR relevant, so that performance and cost comparisons can be made and the best selected.

In conjunction with the Large Coil Project, ORNL will develop basic technology in niobium-titanium superconductors, systems design, magnet winding and fabrication for use by the industrial subcontractors. Thus it will be unnecessary for each industry to duplicate the expensive test facilities and breadth of expertise centered at ORNL.

Testing the large coils for the Compact Torus requires an extensive test facility including cryogenic, vacuum and heavy crane facilities. Both industrial and government-owned facilities are being evaluated for the facility location. Most attractive are those at NASA Plumbrook, Boeing, NASA Houston and ORNL. A decision will be made in the fall of 1976 on the location, so that construction can begin.

Ohmic heating coils promise to be a most difficult task. The coils must cycle from +8 Tesla to -8 Tesla in less than two seconds, while transferring about 1 gigajoule of energy in a high radiation environment. Development begins with the measurement of ac losses and resolution of the various loss mechanisms. As funds permit, sample conductors and model coils will be constructed.

Mirror magnets clearly need high field conductors. While presently the MX superconductor is being developed for 7.5 Tesla operation with niobium-titanium, future mirror experiments will strive to operate at 16 Tesla. Accordingly, multifilamentary niobium-tin superconductors are being pursued for operation in the next generation fusion experiments.

Recent Achievements

As a result of the LLL magnetics program, a large advance in multifilamentary niobium-tin superconductors was made at AIRCO. Three superconductors were developed: one containing 67,507 filaments in 3.2 mm diameter wire, a second with 259,369 filaments in a 9.3 mm by 3.9 mm conductor, and a third with 664,411 filaments in 13.75 mm by 6.0 mm conductor. Each of these conductors had filaments of 5 μ m in diameter and were operated at or above the design values of 1 kA, 3.5 kA and 10 kA, respectively at 12 T. In conjunction with the conductor development a tensile tester was constructed for simultaneously subjecting superconductors to loads of 50,000 pounds, 10,000 amps, and 12 T. An 11 inch bore coil was fabricated from the 1 kA @ 12 T design conductor and has performed beyond the conditions expected from short sample tests. While tests at ORNL show an early onset of resistance in the conductor at nominal strain values, this effect can be corrected by further development.

Another method of mitigating strain effects in such high field brittle superconductors is through the recent development of the MIT-ORNL force-cooled, cabled conductor. Here a relatively open and loose cable is enclosed in a structural tube which supports most mechanical loads. High current densities are possible with full magnetic stability because of the large surface to volume ratio of the cable, and pulsed field losses greatly reduced by transposition of the cable strands. Recently a small coil of one meter length has been tested under forced-flow conditions in a 9 T field and has recovered from quench conditions according to an improved analysis including axial conduction and a more rigorous specific heat formulation. So attractive is this result, that ORNL adopted the design for the EPR design.

A further conductor improvement was made by Battelle Columbus with hydrostatic extrusion of niobium-titanium and niobium-tin superconductors. Extrusion ratios were extended from the current commercial practice of 10:1 to 167:1, which could greatly reduce the manufacturing costs and increase the quality of bronze matrix niobium-tin superconductors. When completed, this technology will be transferred to industry.

While large coil constructions have not yet begun, ORNL has installed 3 meter magnet winding equipment, designed four prototype EPR conductors, and is ready to wind coil segments. A helium liquefier has

been ordered, capable of supplying 866 watts of refrigeration at 3.5 K for support of the Compact Torus and smaller laboratory tests.

Tension-free tokamak coils have been optimized by ORNL to reduce the amount of structure required in the EPR, and quench protection analysis and simulations completed. In addition Cornell has analyzed mechanical instabilities in toroidal field sets and demonstrated the phenomenon with small superconducting magnets.

Plans for the ORNL Large Coil Project are complete and three industries have been contracted for EPR magnet designs. These designs will form the basis for the three meter diameter coils to be constructed for the Compact Torus to support the DMFE FY 1979 decision for the next major step in fusion.

Major Milestones and Funding Summary

The pacing item in magnetic systems is the Large Coil Project at ORNL, which will develop the technology to support a major superconductor tokamak experiment decision in FY 79 for operation by FY 85. This project will construct six coils from industry and ORNL, and possibly from IEA, for assembly into a Compact Torus. An extensive test facility is required soon, so that single coil

tests can be made as the coils are produced. As soon as funding permits, a prototype magnet will be constructed for the TNS. Other near term milestones include the conductor development and magnet design for the MX experiment at LLL.

Fiscal Years
Millions

	1976	1976A	1977	1978	1979	1980	1981	1982	FY 78-82 Total
Operating:	5.20	1.40	13.05	11.56	13.41	17.20	19.84	21.20	83.21
MDF:	-	-	2.40	4.84	7.59	5.80	5.26	8.00	31.49
Equipment:	1.01	0.27	1.60	2.20	4.35	4.90	6.95	7.95	26.35

Major Milestones:

1. Industry to complete conceptual design of EPR magnet Oct. 1976
2. Start industrial design and construction of Compact Torus coils Feb. 1977
3. Complete MX conductor and magnet design Jan. 1978
4. DMFE decision to build TNS and prototype magnet Mar. 1978
5. Completion of Compact Torus coil designs Mar. 1978
6. Complete fabrication of Compact Torus coils Sept. 1979
7. Start construction of TNS prototype Oct. 1979
8. Complete single coil tests for Compact Torus Mar. 1980
9. Test full Compact Torus Sept. 1980
10. Complete TNS prototype June 1981

2. Energy Storage

Presently, large capacitor banks are used to power high-beta experiments such as Scyllac. As the stored energy requirements exceed 100 MJ, it is clear that cost and reliability considerations require alternate approaches. In addition, if a theta pinch reactor is to succeed, it must have a highly efficient energy storage and transfer system which can be provided by superconducting magnets and/or homopolar generators. These same technologies will be necessary for ohmic heating in tokamaks as well.

Objectives and Scope

The energy storage activity is directed toward providing efficient, reliable electromagnetic and electromechanical devices that shape, switch, store, and reclaim the energy flowing through electric and magnetic subsystems of the various fusion concepts. Flywheel motor-generator sets are currently used to provide pulsed power for the larger fusion experiments, and an assortment of battery banks, capacitors, and line-rectifying sources are used for the smaller experiments. In the longer term, more efficient and cost-effective energy storage and switching components must be developed. Principal efforts underway include ohmic heating coil development, superconducting magnetic energy storage systems, advanced inertial (flywheel) motor-generator systems, and efficient fast-switching

components. The program over the next five years will culminate in the demonstration of both pulsed superconducting magnetic energy storage systems and inertial homopolar motor-generator energy storage systems.

Technical Approach

Because superconducting magnets can store energy inductively without loss and have a reasonable transfer efficiency to the compression coils, they are a logical choice for advanced theta pinch concepts. Some losses still occur due to hysteresis in the superconductor and eddy currents in the conductor matrix material. However, by finely dividing the superconductor the hysteresis losses are controlled, and adding high resistance barriers to the conductor matrix decreases matrix eddy current losses to an acceptable level.

Based upon these principals three industrial magnets have been constructed in addition to one by LASL. These coils store 300 kJ for discharge in 1 millisecond at 40 kV. The LASL coil has performed as expected and the others are now being tested. Subsequently the coils must be housed in a non-conducting dewar for a complete systems test.

For longer discharge times (30 msec to 1 sec) a homopolar generator with superconducting windings is attractive. These can be used to power current tokamak toroidal field coils, as developed by Texas, or as a second compression stage in a theta pinch experiment. Alternately they may be useful in a tokamak ohmic heating circuit to act as a transfer capacitor. No other known alternate can provide such efficiency and low cost potential. A significant ancillary need for both magnetic and homopolar energy storage is fast, high voltage power switching.

Recent Achievements

At LASL a 300 kJ superconducting magnet has been designed, fabricated, charged to 10 kA and discharged in 1 msec; the average power delivery during discharge was 300 megawatts! A second coil from the Magnetic Corporation of America was tested to half rating when it suffered some insulation damage. Testing will continue with the magnets from Intermagnetics General Corporation and Westinghouse.

Commercially available AC vacuum circuit breaker switches, which are generally used for one shot circuit protection by utilities, have been successfully tested and utilized in DC operation to 50 kilovolts and 30 kiloamperes. One switch has been mechanically cycled over 70,000 times. These types of switches are economical and adequate for applications in near term fusion experiments. In the long term, the trend will probably be toward solid state switching for reliability and lifetime reasons.

At Texas a 5 megajoule homopolar motor-generator has been designed and fabricated, and is presently undergoing performance testing. Homopolar machines are characterized by high amperage, low voltage outputs. From half speed (2800 RPM) this machine has produced over 500,000 amperes at 30 volts, and the inertial rotor was stopped in less than one second. Besides ultimate use in fusion systems, these types of machines appear to have characteristics that could be utilized in attractive ways for resistance welding of large structures, as has been recently demonstrated with the 5 MJ machine.

Major Milestones and Funding Summary

In setting the major milestones and funding priorities, one must assume that the theta pinch experiments will progress as projected, but possibly on a longer time scale due to recent problems with feedback stabilization on Scyllac. Accordingly the superconducting magnetic energy storage coils will be completed and tested in a reduced system. Because tokamak ohmic heating coils use a similar technology, some LASL effort will be continued in superconductor development for this purpose. In addition a superconducting homopolar is planned for future high beta experiments to be later modified for tokamak ohmic heating.

It is assumed that the TNS will not require a superconducting OH system. Large motor-generator sets will be available instead from the TF power supplies of tokamaks to be phased out around 1985.

However EPR II will definitely need superconducting OH coils and an efficient energy transfer system, incorporating a homopolar as a transfer capacitor. In the meantime support of alternate high beta concepts will require power supplies as alternates to the present capacitor banks.

Fiscal Years
Millions

	1976	1976A	1977	1978	1979	1980	1981	1982	FY 78-82 Total
Operating:	2.20	0.45	1.90	1.9	3.3	4.5	6.0	6.0	21.7
MDF:	-	-	0.40	0.7	0.7	0.5	1.0	2.0	4.9
Equipment:	0.24	0.05	0.25	0.5	0.5	0.7	0.7	1.0	3.4

Major Milestones:

1. Design, fabricate, and test commercially developed 300 kJ superconducting storage coils Oct. 1976
2. Demonstrate a superconducting SFTR prototype system (1 coil) Apr. 1978
3. Complete conceptual design of tokamak OH system Sept. 1979
4. Design, fabricate, and test a superconducting fast discharge (0.03 sec.) 10 MJ homopolar motor-generator (cooperative effort with EPRI) May 1980
5. Complete evaluation of superconductors for pulsed OH coils June 1980
6. Fabricate and test scaled model of OH system (10-50 MJ coil, reversible power supply system, and associated switching) Sept. 1982

C. Plasma Engineering

The Plasma Engineering subelement is actively pursuing the engineering design and component development of fusion plasma support subsystems for near-term fusion experimental devices and ultimately for fusion reactor systems. Within the Plasma Engineering subelement five, major technical areas are being pursued:

- Neutral Beam Development
- Alternate Heating Technology
- Direct Energy Conversion
- Vacuum Component Development
- Plasma Maintenance and Control Systems

Within each of the five, major technical areas the principal objectives are to provide for the definition, development, design, fabrication, testing and operation of engineering subsystems which will satisfy the particular operating requirements for fusion device applications. In order to meet these objectives, the Plasma Engineering subelement will operate test and development facilities; design, construct and operate prototypical systems; and provide particular components and subsystems to be used on fusion device experiments. Furthermore, the Plasma Engineering program will define those components and/or subsystems

which require further development and will initiate, expand or redirect appropriate developmental efforts. Combined with the other ongoing physics and technology programs which will test the efficacy of the components and subsystems, the Plasma Engineering program will provide the total subsystem design, technology and operating basis.

As defined, the activities within the Plasma Engineering program are primarily user oriented. Therefore, a secondary objective of the development program is to insure close coordination between the user and developer. The users must get the components and subsystems that perform to specification, and the developers must be involved in the design of the confinement device. This is particularly true for questions regarding interfaces where the components and subsystems and the confinement device come together. The user-developer coordination requires a two-way communication and a joint responsibility for the development, fabrication and operation of the complete subsystem.

The final, overall objective of the Plasma Engineering subelement is to maintain close coordination with the various activities of the Systems and Applications Studies subelement. This will help to ensure that the designs, components and subsystems will be developed with realistic requirements and are directed towards specific, long-term applications such as TNS and EPR.

The Plasma Engineering subelement is organized to utilize the expertise of selected institutions which can contribute towards reaching the overall goals. At present the National Laboratories are the principal contributors to the development program. These National Laboratories are carrying through most of the actual development effort as well as participating in design, fabrication, and testing of components and subsystems for use on near-term confinement experiments.

DMFE strives to involve industry in the technical development of fusion reactor subsystems as well as in the area of manufacturing of specific components. This is particularly true in areas where it is possible to utilize a unique industrial capability. Several areas have been identified in which industry is particularly well-suited to participate. These are areas such as: high voltage power supplies; switch tube and klystron development; cryogenic equipment; electrode manufacturing; and other ion positive and negative source concepts. Efforts are underway or are being initiated at appropriate industrial contractors.

Several universities presently are participating in support of the overall development program. The areas of university work are, in general, those of basic research, measurement and analysis, and small-scale design and testing. However, the greatest contribution of university effort is in the area of training

of students. When their training is completed, these students are then available to work in the rapidly expanding fusion power program. The development program will expand in the area of university involvement as additional needs and expertise become identified.

Each of the five technical areas within the Plasma Engineering subelement is discussed in the following sections. A budget summary of the Plasma Engineering Branch activities is shown in Table IV-3.

TABLE IV-3

Plasma Engineering
Budget Summary

		Fiscal Years Millions								FY78-82 Total
		1976	1976T	1977	1978	1979	1980	1981	1982	
Neutral Beam	oper.	8.39	3.170	14.00	15.50	17.5	18.1	20.5	24.0	95.60
	equip.	2.22	0.360	1.67	2.10	4.5	4.0	3.0	3.0	16.60
Alternate Heating	oper.	1.49	0.450	3.50	2.80	3.5	3.5	4.5	5.0	19.30
	equip.	0.07	0.025	0.23	0.75	1.0	1.0	2.0	1.0	5.75
Direct Energy Conversion	oper.	0.20	0.050	0.40	0.50	0.8	0.8	1.0	1.0	4.10
	equip.	0.02	0.005	0.08	0.05	0.2	0.3	0.5	0.5	1.55
Vacuum Components	oper.	0.03	- 0 -	0.50	0.70	1.2	1.3	1.3	1.5	6.00
	equip.	- 0 -	- 0 -	0.07	0.08	0.3	0.3	0.3	0.3	1.28
Plasma Maintenance & Control	oper.	- 0 -	0.040	1.30	1.50	2.0	2.3	2.5	3.0	11.30
	equip.	- 0 -	0.025	0.10	0.12	0.5	0.5	0.7	0.8	2.62
Totals	oper.	10.11	3.710	19.70	21.00	25.0	26.0	29.8	34.5	136.30
	equip.	2.31	0.415	2.15	3.10	6.5	6.1	6.5	5.6	27.80

Key milestones in the five major areas of the Plasma Engineering subelement which are required for TNS are summarized below:

- Neutral Beam Development
 - Define beam requirements and development plan for TNS April 1977
 - Operate 150 kV, 1A, 10 msec. negative ion beam system June 1977
 - Operate 200 kV, 25A dc test facility Oct. 1977
- Alternate Heating Technology
 - Define rf heating system technology requirements for TNS Oct. 1976
 - Complete rf heating system preliminary design for TNS Oct. 1980
- Direct Energy Conversion
 - Operate direct converter in conjunction with 100 keV, 1 MW ion beam June 1977
 - Define beam-line direct converter requirements for TNS Oct. 1977
- Vacuum Component Development
 - Define vacuum pumping requirements and development plan for TNS April 1977
 - Construct and operate large scale cryocondensation vacuum system on a neutral beam test facility Oct. 1977

- Test cryogenic vacuum systems in radiation environment June 1978
- Simulate and operate TNS vacuum pumping system Oct. 1979
- Plasma Maintenance and Control Systems
 - Define diverter requirements and development plan for TNS Oct. 1977
 - Define fueling requirements and development plan for TNS Oct. 1977
 - Simulate and test TNS plasma maintenance and control system June 1980

1. Neutral Beam Development

The Neutral Beam Development effort is devoted to the development of neutral particle injection systems for specific tokamak and mirror applications. At present, neutral beam injection is the principal method of auxiliary plasma heating for these confinement methods. Near-term experimental fusion devices will require appropriate and fully integrated neutral beam injection systems. Furthermore, it is probable that longer range fusion reactors will also require appropriate neutral beam injection systems. The neutral beam development program will provide for the development, design, and prototype systems for neutral beam injection systems with the required characteristics of beam energy, power, and pulse length.

Objectives and Scope

The principal objective of the Neutral Beam Development Program is to develop neutral beam injection systems for use on near-term confinement devices such as PLT, Doublet-III, MX and TFTR. In addition to direct, confinement device support, the development program must provide a basic development effort in order to meet longer term requirements for TNS, EPR, and beyond. The development program, therefore, is primarily user oriented, wherein the developers, users, designers and DMFE, working jointly, determine the specifications and parameters required for a particular neutral beam injection system. These specifications and parameters along with the project schedules then determine the specific goals and timing required of the development effort.

In order to support present and future confinement devices, a vigorous basic development program is required. This is particularly true at the present time in the area of negative ion source technology. A number of methods for the production of negative ions have been suggested, and several of the more promising concepts are being pursued. Other areas of basic, supporting beam development which are being pursued as funding permits include: alternative neutralization schemes; beam energy recovery; and atomic and molecular species control.

In order to provide complete, reliable neutral beam systems, close attention must be given to the technological and engineering developments necessary for the various subsystems of a neutral beam injector. This includes such items as the components in the electrical, mechanical, diagnostic and control subsystems which are necessary for the operation of the neutral beam system. Items in this area include: cheaper and more reliable power supplies; high speed vacuum systems; and non-intercepting neutral beam diagnostics. Neutral beam control components to be designed and specified include closed loop, active feedback techniques to time and operate multiple beam lines in a coordinated manner.

The final objective of the program is to provide for manufacturing support and technology transfer to industry for the overall neutral beam program. The particular goal is to identify, educate and qualify manufacturers who ultimately will produce reliable neutral beam system hardware to stated specifications and in the required quantities.

Technical Approach

The Neutral Beam Development Program is a broadly based technological effort aimed at providing suitable neutral beam injection systems for use on plasma confinement devices and fusion power reactors. As such, the development program is a multidisciplined one which encompasses not only

the engineering and technology aspects but also some of the plasma physics and systems engineering aspects as well. Therefore, it is necessary that the structure and content of the development program be clearly formulated to assure that the necessary coordination and communication is maintained so that the program goals may effectively and efficiently be met.

A number of technological problem areas must be explored and solutions obtained before large, reliable, and efficient neutral beam systems can be designed, fabricated, and operated routinely. Specific development efforts in some of the major technological problem areas are to provide: high quality and high efficiency ion sources; improved ion optics and beam focussing; more efficient and more vacuum compatible neutralizers; high power density beam diagnostics and targets; improved electrode and insulator materials for operation in a radiation environment; high-speed, high-throughput vacuum systems; safe and reliable high power electrical systems; and instrumentation and control systems to operate multiple beam systems. All of these technological problem areas are addressed within the various elements of the development program. In this manner complete engineering designs can be provided for neutral beam injection systems which are appropriate to the particular confinement device application.

Several types of key programmatic milestones have been established for the development program. One is the operation of required test and development facilities; a second is the design, fabrication, and testing of particular neutral beam hardware for confinement experiments. In addition, milestones relating to the establishment of particular technologies have been identified.

One of the key items within the development program is the availability of adequate and timely test and development facilities. These test facilities are the pacing milestones in the development program. Although much of the development work can be and is performed on low-power, small-scale test and development facilities where it is technically reasonable and cost effective, it is essential that full-scale, full-power testing of neutral beam system modules be included in the development program. Testing of such modules must be performed on a timely basis. That is, sufficient testing and development time must be allocated within the development schedule for test stand and prototype operation before it is needed for operation on the confinement devices. This time is necessary in order to allow for several iterations and turn-arounds before the design of the neutral beam system is fixed.

Next generation neutral beam systems will require beam energies in the range of 80-150 keV. These neutral beams are required for confinement experiments such as TFTR, MX and Doublet-III. Therefore, the two large test stands presently under construction have been designed to cover this range. Specifically, the maximum operating parameters of these test stands are:

ORNL	150 kV, 50 A, steady-state
LLL	200 kV, 25 A, steady-state, or
	100 kV, 100 A, 5 sec.

As the development program proceeds to higher energies and higher powers, these test stands become larger and more complex. This in turn means that the test facilities become more costly and take longer to bring on line. Therefore, it is essential that the specifications for the required neutral beam systems be determined in a timely manner; i.e., in the conceptual design stage, the neutral beam parameters must be adequately specified so as to define the appropriate development program.

Beam systems for experimental devices to be operational in the 1985 time frame are presently thought to be in the 300-400 keV range. Therefore, neutral beam test and development facilities will be provided for this extrapolation by early 1981. It is anticipated that one of the existing large test facilities will be upgraded for this effort.

The ongoing development effort in plasma sources, accelerator structures and subsystems is the general basic effort of improvement and optimization of neutral beam systems. All of the sub-tasks in these basic efforts are brought together and are tested on the particular test and development facilities. Therefore, this development effort is an iterative one in which new scalings, new ideas and new concepts will be operated on the test facilities and results will be fed back to the appropriate sub-task area. In this manner, the test facilities serve as a focus for the ongoing development effort.

Recent Achievements

- | | |
|---|------------|
| ● Operate neutral beam injection systems on ATC | Aug. 1974 |
| ● Operate 12 neutral beam injectors on 2XII-B | Sept. 1974 |
| ● Operate 4 neutral beam injectors on ORMAK | Jan. 1975 |
| ● Operate 1 A direct extraction negative ion source | May 1975 |
| ● Operate 60 kV, 60 A neutral beam development test stand | Sept. 1975 |
| ● Operate pulsed 80 A ion source at 40 kV | Sept. 1975 |
| ● Completed final conceptual designs for TFTR Neutral Beam Systems | Sept. 1975 |
| ● Complete first phase of neutral beam I&C design and development package | Jan. 1976 |

- Initiated detailed design and fabrication of neutral beam lines for PLT Feb. 1976
- Operated first computer control/automatic conditioning of neutral beam lines at LBL March 1976

Funding Summary and Major Near-Term Milestones

	Fiscal Years								FY78-82 Total
	Millions								
	1976	1976T	1977	1978	1979	1980	1981	1982	
Base Program Operating	5.34	2.00	10.20	12.0	14.5	16.1	18.5	22.0	83.1
Major Device Fabrications	3.05	1.17	3.80	3.5	3.0	2.0	2.0	2.0	12.5
Total Operating	8.39	3.17	14.00	15.5	17.5	18.1	20.5	24.0	95.6
Equipment	2.22	0.36	1.67	2.1	4.5	4.0	3.0	3.0	16.6

Milestones

- Operate first PLT neutral beam system July 1976
- Operate 80-150 kV, 20A, 0.5 sec. test facility July 1976
- Operate 150 kV, 50 A, dc test facility Oct. 1976
- Deliver PLT injection systems Oct. 1976-March 1977
- Define beam requirements & development plan for TNS April 1977
- Operate 150 kV, 1 A, 10 msec. negative ion beam system June 1977

● Select TFTR injection system design	June 1977
● Operate 200 kV, 25 A dc test facility	Oct. 1977
● Operate prototype TFTR injection system	Dec. 1978
● Deliver Doublet-III beam injection systems	1979
● Deliver TFTR beam injection systems	1981
● Deliver MX beam injection systems	1981

2. Alternate Heating Technology

The Alternate Heating Technology program is concerned with providing for the development of plasma heating techniques and technology which will be an alternative or supplement to neutral beam heating. At present, this activity is concentrated on the development of radiofrequency and microwave technologies suitable for plasma heating experiments on present and next generation fusion experiments. Also, this activity includes the development of shock and compression heating and other technology such as magnetoacoustic heating suitable for pinch devices.

Objectives and Scope

The objectives of the Alternate Heating Technology program are to provide the technological development and design expertise necessary to design, fabricate, and operate radiofrequency, microwave, shock and compression heating systems on experimental fusion devices. The focus of this effort is

on the present and next generation experiments such as EBT, Scyllac, PLT, PDX, ISX and possibly TFTR. In this manner, a viable alternate heating technology base will be maintained as a backup or supplement to neutral beam heating.

The Alternate Heating Technology program will provide the basic operating techniques for an alternate plasma heating system for an Experimental Power Reactor (EPR). This will lead to well-defined conceptual designs of alternative plasma heating systems for ultimate fusion reactor applications. For example, present thinking indicates that a radiofrequency plasma heating system for a tokamak EPR will require in the range of 50-70 MW of steady-state power. The coupling structures, waveguides, and transmission lines will be exposed to the radiation fields present in a reactor. Therefore, engineering designs and components must be developed beyond the present state-of-the-art for these systems.

Technical Approach

Radiofrequency (RF) heating of plasmas offers certain advantages and is a major alternative or supplement to neutral beam heating. Development work on RF heating presently is being carried out at

the lower hybrid frequency (LHF), the ion cyclotron frequency (ICF), and the electron cyclotron frequency (ECF).

The engineering advantages of working at the LHF are two-fold. First, there is a significant amount of power available from commercial tubes in the frequency range that is required for fusion research devices or reactors. For example, klystrons are available in this frequency regime with an output power in the 500 kW range. Second, for some conditions, power at this frequency can be transmitted through the vacuum vessel wall by open-ended wave guides. The use of wave guides eliminates the need for high-voltage insulators at the first wall near the plasma. Such insulators would be required with inductively- or capacitively-coupled radiofrequency systems.

Radiofrequency heating experiments are being conducted at the lower hybrid frequency on the ATC device at the 250 kW level. Plans are in progress to incorporate LHF heating into the next generation fusion device experiments such as PLT, PDX, and ISX. Radiofrequency systems for applications on these experiments will be in the multimegawatt regime.

The principal engineering advantage of operating at the ICF is also that large blocks of RF power are readily available from commercially available power tubes. The principal disadvantage is that

antennas or similar coupling structures are probably required inside the vacuum chamber in the plasma environment.

Radiofrequency heating experiments are being conducted at the ion cyclotron frequency on the ATC device. These experiments will serve to corroborate earlier results as to the efficiency of plasma heating using this technique. Plans are being prepared to incorporate ICF heating into the next generation fusion device experiments such as PLT or PDX. Radiofrequency systems for these applications will also be in the multi-megawatt regime. Design and development of radiofrequency systems for applications at both the LHF and the ICF are major milestones for the Alternate Heating Technology program. The results of this design and development coupled with the basic theory and experimental results will point the way toward RF heating of fusion reactors such as EPR.

A similar effort to develop and test plasma heating via electron cyclotron resonance heating (ECRH) is being conducted and includes testing on the EBT device. The EBT currently is operating with 60 kW of combined 10.6 and 18.0-GHz microwave power. The development of this technology represents a significant milestone in the alternate heating effort. The ECRH technique can, in principal, be used to heat the plasma in bulk or as an adjunct to another heating mechanism for additional plasma control.

The long-range ECRH effort encompasses the development of multi-kilowatt, millimeter wave-length microwave power sources and coupling circuits. A major milestone of the Alternate Heating program is to develop a high power (200 kW), high frequency (120 GHz), steady-state microwave power source. The design and development of this microwave power source is to be performed by industry to laboratory specifications.

Shock heating and compression heating systems are required for theta pinches, toroidal Z pinches, and possibly high-beta tokamak experiments. The principal effort in this task is development of components and subsystems which will satisfy the heating system requirements. Materials such as ceramics which can withstand both the high neutron flux and the plasma particle flux must be developed if these systems are to be successful. In addition, this program will pursue the general development of high voltage, high power, high coulomb components. For example, LASL is developing a Marshall coil system and a power crowbar system for the next generation of experiments. These components will have utility in many areas of MFE.

Other potential methods of plasma heating such as lasers and electron beams are in the research stage and may be selected for hardware development if technical progress warrants. The program plan

assumes that plasma heating techniques other than or in addition to neutral beams will be required. Therefore, the program includes technology development and large scale testing of appropriate devices in order to assure their quality, performance, reliability and lifetime.

Recent Achievements

- Operate 100 kW ICF system on ST Jan. 1974
- Operate 125 kV spark gap and capacitor components Jan. 1975
- Operate 30 kW microwave system on EBT April 1975
- Operate 250 kW LHF system on ATC Sept. 1975

Funding Summary and Major Near-Term Milestones

	Fiscal Years Millions								FY78-82
	1976	1976T	1977	1978	1979	1980	1981	1982	Total
Operating:	1.492	0.450	3.50	2.80	3.5	3.5	4.5	5.0	19.30
Equipment:	0.070	0.025	0.23	0.75	1.0	1.0	2.0	1.0	5.75

Milestones

- Evaluate LHF and ICF plasma heating on ATC July 1976
- Define radiofrequency heating system technology requirements for TNS Oct. 1976

● Fabricate Marshall Coil	Nov. 1976
● Test components for 200 kV shock heating circuit	June 1977
● Evaluate power crowbar system	Sept. 1977
● Operate prototype 25 GHz microwave source for EBT	Oct. 1977
● Install and operate multi-megawatt rf heating system on PLT/PDX	Oct. 1978
● Complete rf heating system preliminary design for TNS	Oct. 1980

3. Direct Energy Conversion

The Direct Energy Conversion activity is concerned with the recovery and conversion of the energy of charged particles in fusion plasmas and ion beams directly into electricity. The ability to utilize such an energy conversion system would lead to increasing the overall efficiency of fusion power plants and neutral beam injection systems. Thus, there are both economic and efficiency incentives for the development of a direct energy conversion technology.

Objectives and Scope:

The principal objective of the Direct Energy Conversion program is to develop the components and subsystems required to operate direct energy conversion systems of fusion device experiments and neutral beam systems. In addition, a secondary objective is to develop the design experience and

capability with which to implement direct energy conversion systems on new fusion experiments or different applications. In this manner, the Direct Energy Conversion program is an auxiliary developmental effort in support of other technological programs.

The Direct Energy Conversion program is a relatively small development effort in support of mirror fusion reactor programs and neutral beam development programs. However, at least conceptually, direct converter technology could apply to other fusion concepts such as pinch devices or tokamaks. For example, a direct converter may be an integral part of tokamak diverter system.

The scope of the Direct Energy Conversion program will be maintained so as to provide at least small-scale hardware tests and conceptual design efforts. In this manner, the program will maintain its viability to provide engineering design data and system design concepts.

Technical Approach

The reason for developing direct energy conversion techniques is to raise the efficiency of the power handling equipment for fusion reactors and neutral beam injection systems. The basic principles of direct energy conversion have been demonstrated in laboratory experiments, and the program now is turning to the development of practical direct conversion systems.

Three applications for direct energy recovery have been identified for both near- and intermediate-term applications:

- (1) recovery of the energy of unneutralized ion beams to make neutral beam systems more efficient and thus extension to higher energies with neutral beams, production of less waste heat and improvement in charged particle beam dump;
- (2) recovery of the energy of plasma fuel ions which leave the plasma in a fusion reactor; and
- (3) recovery of the energy of fusion products (e.g., He^{++}) in the exhaust of a fusion reactor.

All three of these applications will increase the operating efficiency of the overall fusion reactor system.

Ion beam direct conversion experiments will begin in the second half of 1976 on the LBL 80-150 keV neutral beam test facility. In this facility direct conversion equipment can be operated for beam powers of approximately 1 MW for pulse times of up to 0.5 sec. The goal of this effort is to develop beam direct converters as fast as the neutral beam systems will be developed so that overall system designs can be made. This work will be closely coordinated with the neutral beam development efforts.

The direct conversion facility will be modified so as to test plasma direct converter concepts at full voltage, full power density and for steady-state conditions expected in reactor applications.

These tests will demonstrate:

- (1) in-situ voltage holding;
- (2) adequacy of radiation cooling; and
- (3) materials testing under mirror reactor-like conditions.

This effort will be closely coordinated with the ongoing fusion reactor experimental and advanced design efforts.

Recent Achievements

- Operate multi-stage direct converter at predicted efficiency of about 85% July 1974
- Operate two-stage direct converter at predicted efficiency of about 65% Jan. 1975
- Operate direct converter in conjunction with ion beam system Jan. 1976

Funding Summary and Major Near-Term Milestones

	Fiscal Years Millions								FY78-82
	1976	1976T	1977	1978	1979	1980	1981	1982	Total
Operating:	0.200	0.050	0.40	0.50	0.8	0.8	1.0	1.0	4.10
Equipment:	0.015	0.005	0.08	0.05	0.2	0.3	0.5	0.5	1.55

Milestones

- Design beam-line direct converter for 120 keV beams at 5 kW/cm² Oct. 1976
- Operate direct converter in conjunction with 120 keV, 1 MW ion beam June 1977
- Define beam-line direct converter requirements for TNS Oct. 1977
- Operate plasma direct converter on mirror device (BB-II) Oct. 1978
- Assess direct converter technology for tokamak DEMO June 1979
- Complete design of a plasma direct converter for MX Oct. 1980
- Deliver MX beam-line converter June 1981
- Deliver MX plasma direct converter June 1982

4. Vacuum Component Development

Fusion reactors and several reactor subsystems will require high-speed, high-throughput clean vacuum pumping systems. In addition, these vacuum systems must be compatible with the plasma system and also operate reliably in the radiation environment. The Vacuum Technology program will provide the basic engineering design data and systems tests to specify near-term fusion experiment and ultimately fusion reactor vacuum systems.

Objectives and Scope

The objective of the Vacuum Component Development program is to provide the engineering design and component development of vacuum systems to meet the requirements of the fusion reactor systems. A fusion vacuum system must handle various gas species at the required pumping speed and throughput under either pulsed or steady-state operation. Such a system must perform reliably in an environment of energetic and charged particles. Furthermore, size, space and geometry requirements may be imposed by the interfacing systems or components of a fusion system.

The Vacuum Component Development program will provide the required engineering design data for qualification of components and systems for both near-term experiments and long-term fusion reactors. The program will be responsive to new requirements and be closely coordinated with other engineering design efforts.

Technical Approach

The Vacuum Component Development program is focussed on meeting the design vacuum requirements of magnetic confinement experiments and neutral beam systems. This program provides for the development of vacuum technology to meet the needs of the post-TFTR fusion reactors operating under long-pulse or steady-state conditions.

It is projected that all fusion concepts will require demanding vacuum systems and components for reactor operation. Specifically, vacuum systems capable of pumping gas loads on the order of 100 torr-litre/sec of hydrogen isotopes at pressures of 10^{-5} to 10^{-4} torr must be developed. Gas loads in this regime will be encountered in the next generation neutral beam injection systems. Additional pumping problems will be encountered when DT reacting plasmas become a reality. For example, fusion plasmas will produce a helium gas load due to alpha particle production. There are only a limited number of methods available for pumping helium; and the attendant deuterium gas load will compete in all of these methods for pumping capacity. Furthermore, reacting DT plasmas also will increase irradiation of the pumping surfaces.

The Vacuum Component Development program will design, fabricate, test and evaluate small-scale and/or prototype vacuum systems and components in order to meet the program objectives. The present program

focuses on wall pumping techniques such as cryocondensation, cryosorption, cryotrapping, and bulk gettering for very high gas loads. The program will investigate these pumping techniques and will develop the basic design data, capabilities, and limitations of each. Development and documentation of procedures such as leak hunting, degassing, and regeneration also will be carried out as part of the development program. Development and testing of other vacuum hardware such as valves, flanges, seals, etc. will be performed to support specific vacuum system designs as needed.

Recent Achievements

- Operate 1.5×10^5 litre/sec. D_2 cryocondensation pump Jan. 1976
- Operate 1.2×10^5 litre/sec. H_2 cryocondensation pump manufactured by industry May 1976
- Operate cryocondensation pump on high energy beam line June 1976

Funding Summary and Major Near-Term Milestones

	Fiscal Year Millions								FY78-82
	1976	1976T	1977	1978	1979	1980	1981	1982	Total
Operating:	0.03	- 0 -	0.50	0.70	1.2	1.3	1.3	1.5	6.00
Equipment:	- 0 -	- 0 -	0.07	0.08	0.3	0.3	0.3	0.3	1.28

Milestones

- Define vacuum pumping requirements and development plan for TNS April 1977
- Provide basic design data for cryocondensation and cryosorption vacuum systems Oct. 1977
- Construct and operate large scale cryocondensation vacuum system on a neutral beam test facility Oct. 1977
- Test operation of titanium bulk getter pump Jan. 1978
- Test cryogenic vacuum systems in radiation environment June 1978
- Assess vacuum technology for tokamak June 1979
- Simulate and operate TNS vacuum pumping system Oct. 1979
- Operate test model for steady-state vacuum pumping system for MX Jan. 1980

5. Plasma Maintenance and Control

The Plasma Maintenance and Control program includes the engineering design and component development of plasma fueling and impurity control systems. As such, this program provides the engineering development of those systems and components necessary to sustain and control the plasma in a fusion reactor.

Objectives and Scope

If a fusion power reactor is to be operated for burn times significantly longer than the average particle confinement time, it will be necessary to refuel the reactor while it is operating. Because only a small fraction of the fuel will react before it is lost, methods are required to divert and collect these non-reacting plasma ions as well as the fusion reaction products. The principal objective of the Plasma Maintenance and Control program therefore is to develop and test components and systems for plasma fueling and sustenance for a fusion reactor.

For plasma fueling technology, the Plasma Maintenance and Control program provides for the development of particular fueling hardware, provides an assessment of the various fueling techniques, and provides engineering designs and tests in order to determine capabilities and limitations for the various fueling approaches. To meet these objectives the program now focusses on the development of fueling hardware with capabilities to meet the needs of present and next generation fusion reactor experiments. This development and testing will generate the engineering data base and design experience required to provide fueling systems for ultimate fusion reactors.

Similarly for diverter systems, the Plasma Maintenance and Control program provides engineering design data as input into reactor conceptual designs. Furthermore, small-scale tests and diverter

assembly prototypes will be performed as they become necessary. In this manner, the engineering data base and design expertise is generated so as to provide adequate diverter systems for fusion reactors.

Technical Approach

Within the Plasma Maintenance and Control program, one of the sub-tasks currently under investigation is the plasma fueling effort. Several techniques for plasma fueling have been suggested, such as: solid pellets, neutral particle beams, cluster beams, plasma guns, liquid jets, and gas blankets. At present, solid pellets of frozen deuterium and tritium are expected to meet the fueling requirement for tokamak fusion reactors.

The present and near-term development program for solid pellet fueling systems is directed toward developing controlled and reliable methods of pellet formation. In addition, various candidate acceleration techniques include the gas dynamic or jet technique, rotating mechanical systems, electrostatic accelerators, and laser acceleration systems. These techniques will be studied using small-scale and prototype hardware in order to determine the operating characteristics, capabilities, and limitations associated with each technique.

Also, it is necessary to determine where the fuel will be deposited within the plasma. This in turn requires experimental knowledge of the pellet ablation rate versus pellet speed and size. Prototype pellet injection systems will be built and installed on appropriate fusion device experiments in order to determine the detailed plasma fueling mechanisms. This work will be closely coordinated with the ongoing confinement experiment programs.

If diverter systems are required for fusion reactors, such systems will place severe requirements on the particle collection and vacuum pumping devices for such a system. In addition, these diverter systems will be required to operate in a high radiation environment. Conceptual designs for such diverter systems will be prepared, and small-scale tests and prototypes will be performed as necessary.

Recent Achievements

- | | |
|--|-----------|
| ● Operate first generation deuterium pellet injector | July 1975 |
| ● Test pellet fueling device with hydrogen on ORMAK | Sept.1975 |

Funding Summary and Major Near-Term Milestones

	Fiscal Year Millions								FY78-82 Total
	1976	1976T	1977	1978	1979	1980	1981	1982	
Operating:	- 0 -	0.040	1.30	1.50	2.0	2.3	2.5	3.0	11.30
Equipment:	- 0 -	0.025	0.10	0.12	0.5	0.5	0.7	0.8	2.62

Milestones

- Test prototype pellet injection device on ORMAK Jan. 1977
- Define diverter requirements and development plan for TNS Oct. 1977
- Demonstrate rotating mechanical pellet accelerator Oct. 1977
- Establish limits for electrostatic pellet acceleration Oct. 1977
- Define fueling requirements and development plan for TNS Oct. 1977
- Operate pellet injection device on PLT and ISX or ORMAK-UG June 1978
- Operate pellet injection device on PDX and/or Doublet-III Jan. 1979
- Assess technology of plasma refueling and impurity control for tokamak DEMO June 1979
- Simulate and test TNS plasma maintenance and control system June 1980

D. Fusion Reactor Materials

Materials represent one of the major long-lead time problem areas for power producing fusion systems. Fusion reactors present their own special materials problems related to, but often separate from, those of LMFR's and other systems. The most severe of these deals with the effects of 14 MeV neutrons and other high energy particles generated in fusion reactors.

This radiation not only results in increased bulk radiation effects (displacement damage, void formation, helium embrittlement) but gives rise to a whole new set of surface related effects including neutron and charged-particle sputtering, blistering, and chemical sputtering. Such effects are known to exist, but there is only a modest knowledge about their magnitude, reproducibility, variability with materials, and energy dependence. Other areas that require investigation include potential coolant and blanket materials, compatibility with structural components, welding and fabrication techniques, nondestructive testing, high temperature design, and adequate electrical insulators. A part of the Reactor Materials Program is the development of radiation facility concepts for testing of materials and components.

The objectives of the fusion Reactor Materials Program are to develop the materials and materials technology for commercial fusion power generation. This includes the development

of new radiation resistant first wall/structural alloys, as well as the development and testing of other materials such as insulators, advanced superconductors, moderators, breeding materials, and materials for heat conversion systems.

The Reactor Materials Program is divided into five research and development areas as follows. These areas are a major departure from previous Five Year Plans not only in title but in the work to be accomplished under each technical area.

1. Alloy Development for Irradiation Performance
2. Plasma - Materials Interaction
3. Special Purpose Materials Development
4. Damage Analysis and Dosimetry
5. Radiation Facilities Development and Operation

The management approach is management by objectives with major objectives defined by the Materials and Radiation Effects Branch relative to the prime DMFE goals. Detailed milestones and program plans will be developed by technical area Task Groups composed of laboratory and contractor personnel, both from the materials research and engineering communities as well as from the design community. The Task Groups will make programmatic recommendations to DMFE for implementation at the laboratory and contractor organizations,

and the contractors in turn work toward specific milestones which are defined in the Task Group Program Plans and incorporated into the 189a documentation. Four Task Groups in the following subject areas will be convened: First Wall Alloy Development, Plasma-Materials Interaction, Radiation Damage Analysis and Fundamental Studies, and Special Purpose Materials.

An overview of the funding requirements for the next five years for the Fusion Reactor Materials Program is shown in Table IV-4.

1. Alloy Development For Irradiation Performance

Objectives and Scope

The objective of the Alloy Development for Irradiation Performance subprogram is to provide the materials development and application for those structural materials which are subject to significant radiation damage.

The prime technical objective is the development of a structural material for the first wall and structural elements for the blanket and shield of a commercial fusion power reactor.

Secondary objectives, intermediate in time and technical difficulty are specific tasks directed towards the prime objective that will provide a series of material development and optimization steps designed to satisfy the data requirements for intermediate fusion power systems,

TABLE IV-4
FUSION REACTOR MATERIALS BUDGET SUMMARY

		<u>Fiscal Years</u> Millions								78-82
		1976	1976T	1977	1978	1979	1980	1981	1982	Total
Alloy Development for Irradiation Performance	Operating	1.39	0.36	2.96	5.8	6.8	8.7	11.0	13.0	45.3
	Equipment	0.28	0.03	0.17	0.33	0.9	1.0	1.2	1.3	4.73
Plasma-Materials Interaction	Operating	1.63	0.39	2.05	2.8	3.6	4.5	5.0	5.0	20.9
	Equipment	0.41	0.08	0.37	0.43	0.5	0.5	0.6	0.6	2.63
Special Purpose Materials Development	Operating	1.17	0.26	0.81	1.0	1.2	1.8	2.3	2.8	9.1
	Equipment	0.24	0.02	0.12	0.08	0.1	0.2	0.2	0.3	0.88
Damage Analysis and Dosimetry	Operating	0.85	0.26	0.61	1.0	2.0	2.2	2.5	2.5	10.2
	Equipment	0.18	0.04	0.10	0.03	0.2	0.2	0.3	0.3	1.03
Radiation Source Development and Operation	Operating	1.83	0.48	2.92	5.4	6.4	5.8	5.5	7.2	30.3
	Equipment	0.29	0.04	0.30	1.03	1.2	0.7	0.7	0.8	4.43
Total:	Operating	6.87	1.75	9.35	16.0	20.0	23.0	26.3	30.5	115.8
Total:	Equipment	1.40	0.21	1.06	1.90	2.9	2.6	3.0	3.3	13.7

The scope of these activities includes (a) the definition of material requirements that are needed to satisfy fusion power system design goals, including the Experimental Power Reactor (EPR), the Demonstration Plant (DEMO) and Commercial Fusion Reactors, (b) the evaluation of existing materials to meet those goals, (c) the development of new materials where they are required to achieve those goals, and (d) the development of the materials radiation data base required for design, construction and operation of fusion power systems.

Technical Approach

Several major paths for alloy development of a first wall/structural material are outlined below. The importance of achieving the objective of a radiation resistant alloy and the relatively long lead time to commercial fusion power make it both rational and imperative that multiple development paths be followed. Neutron irradiation of materials leads to displacement damage and transmutant production which affect the engineering properties of structural materials. A fusion reactor spectrum contains about 25% of neutrons above 10 MeV as compared to fission reactor spectra where the number of neutrons above 2 MeV is very small. This results in greater damage to materials in the fusion spectrum and hence more severe service conditions.

A four-path program that is focused on the commercial fusion power goal, and that will make maximum use of both broadly innovative concepts and relatively well established materials technologies, will be followed.

The paths contain interim objectives that reflect aggressive but realistic development and use of irradiation test facilities. In addition, at least two of these paths have interim objectives that will provide alloy selection and data for the intermediate fusion power goals of experimental and demonstration power reactors.

Path A is directed to development of the optimum class of austenitic alloys. Path B is aimed at the higher strength, higher temperature alloy development in the Fe-Ni-Cr alloy system (i.e. superalloys). Both A and B can be tested to end-of-life damage levels in fission reactors with confirmation in d(Li,n) neutron test facilities.

Path C will address the reactive and refractory alloy option. The initial phase on this path will be a screening activity designed to screen materials and eliminate those that are unsuitable through use of fission reactors, available neutron sources, and simulation tools. Initial development of prime candidates will be accomplished using d(Li,n) facilities. Final alloy optimization engineering data acquisition will be done in a Materials Fusion Test Reactor as outlined in DMFE's Long Range Planning document.

Path D will be established through open solicitation of innovative material development and application concepts. This could include minimum activation materials, composite or graded materials or other imaginative ideas that offer the possibility of reduction to engineering practice. The timing of the overall alloy development program is given in the section entitled Milestone and Funding Summary.

Recent Achievements:

. Stainless steel alloys 316 and 316 Ti modified have been examined after irradiations in HFIR to displacement damage levels up to 60 dpa and transmutant levels of more than 4000 appm He. These levels exceed approximately 5 and 10 year exposures, respectively, in a fusion reactor with a 1 MW/m^2 wall loading. Both titanium and cold work reduce the adverse effects of irradiation on the properties and behavior of the alloys.

These preliminary results indicate that a cold worked stainless steel would still have useful engineering properties after about 5 MW-years/m^2 in the fusion reactor environment.

. Niobium and vanadium alloys irradiated in HFIR show little loss of ductility (at relatively low He levels) and no swelling.

. Results from RTNS irradiations of copper and niobium indicate that, for threshold phenomena, 14 MeV neutrons create about ten times as much displacement damage as an equivalent number of fission reactor neutrons; however, displacement damage theory is able to account for these differences to within a factor of two or less.

Irradiation of an EBR II experiment was initiated. The test assembly contains an array of candidate alloys that have had helium added by alpha particle injection.

Major Milestones and Funding Summary

Fiscal Years - Millions

Budget: Alloy Development for Irradiation Performance	1976	1976T	1977	1978	1979	1980	1981	1982	FY78-82 Total
Operating	1.39	0.36	2.96	5.8	6.8	8.7	11.0	13.0	45.3
Equipment	0.28	0.03	0.17	0.33	0.9	1.0	1.2	1.3	4.73

Milestones:

- . Establish Task Group on First Wall Alloy Development..... August 1976
- . Establish preliminary target goals to meet the materials requirements of commercial fusion power..... March 1977
- . Complete alloy development to meet materials requirements of commercial fusion power..... 1993

Detailed alloy development milestones follow to illustrate the approximate timing of each development path.

a) Path A Austenitic Alloys

Complete Initial Optimization of Composition and Structure (OPT-1)	1983
Establish Maximum Performance Level of OPT-1	1988
Complete Final Alloy Optimization	1988
Establish Maximum Performance Level of Alloy Class	1991

b) Path B High Strength/High Temperature Fe-Ni-Cr Alloys

Complete Initial Optimization of Composition and Structure (OPT)	1983
Establish Maximum Performance Level of OPT-1	1988
Complete Final Alloy Optimization	1988
Establish Maximum Performance Level of Alloy Class	1991

c) Path C Reactive/Refractory Alloys

Complete Initial Screening Phase - (Eliminate losers using simulation testing)	1983
Select Prime Candidate Alloys (via d(Li,n),DT and fission reactor irradiation)	1988
Initiate Irradiation Testing in Fusion Materials Test Reactor(FMTR)	1990
Complete Initial Alloy Optimization (OPT-1) (via d(Li,n),DT sources,and FMTR)	1993
Establish Maximum Performance Level of OPT-1	1998
Complete Final Alloy Optimization	1999

d) Path D Special and Innovative Materials Concepts

Minimum Activation Concept

Complete Initial Irradiation Test Plan	1983
Complete Candidate Screening (via d(Li,n),DT,and fission reactors)	1988
Evaluate Concept Feasibility	1990

Composite, Graded, and other Innovative Materials Concepts

Issue Request for Proposals	1978
Complete Initial Study Phase	1981
Complete Initial Irradiation Test Plan	1985
Issue RFP for Engineering Development	1985
Complete Initial Engineering Development	1989
Complete Initial Irradiation Testing of Candidate Concepts	1993
Complete Phase II Irradiation Testing of Candidate Concepts	1997
Select Concept	1998

2. Plasma-Materials Interaction

Objectives and Scope

One of the major objectives of the Plasma-Materials Interaction subprogram is to investigate the interaction of the plasma with the wall material in terms of the impurities injected into the plasma. A part of this objective which is longer range is the development of materials' structures which are less susceptible for impurity injections and which maintain structural integrity of the wall for long times.

Specific objectives are:

- To treat surface effects from the standpoints of plasma contamination, wall erosion, and device efficiency
- To evaluate surfaces as part of a completely integrated system consisting of the plasma and its perimeter, the external blanket, subsystems for vacuum pumping, fueling and ash removal, and possibly bumpers or divertors

- . To develop new materials resistant to surface damage in concert with overall alloy development tasks for commercial fusion power

Technical Approach

Surface work is carried out in the following technical areas:

- i) Desorption by a) photons, b) electrons, c) ions and neutrals and d) thermally
- ii) Sputtering by a) hydrogen ions, b) residual gas ions (O^+ , N^+ , etc.), c) helium, d) metallic ions (self sputtering), and e) neutrons
- iii) Hydrogen-wall interaction by a) absorption, b) diffusion, c) surface migration and d) reflection
- iv) Blistering, flaking and surface erosion by a) incident hydrogen, and b) helium from the DT reaction, (n, α) reactions, and tritium decay
- v) Chemical reactions involving a) hydrogen and carbon, b) residual contaminants, c) carbon and metals (e.g. NbC) and d) decomposition, principally of insulators
- vi) Electron emission

Synergistic studies of two of these processes occurring at the same time are now beginning, and will be extended to studies investigating the effects of three or more processes. These studies are designed to simulate the effects of a burning DT plasma.

Recent Achievements

- Neutron sputtering and chunk emission

An upper limit of 5×10^{-4} can now be placed upon the total yield resulting from neutron bombardment, including both atomistic sputtering and the emission of chunks, if any. Participants in the round-robin sample exchange are completing evaluation of their results, and a joint report summarizing this work is expected in the fall of 1976.

- Blistering and flaking

Investigation of these processes has addressed means to suppress them, and also sought an improved fundamental understanding of them. Progress has been made in both areas with identification of optimum temperature ranges for blister suppression, and the types of materials in which blistering is least serious. The relative roles of gas pressure buildup in blister formation and stress gradients resulting from swelling in the near surface region are being clarified.

- Sputtering by hydrogen ions

Recent yields were reported in the USSR and it appears that the results are in reasonable agreement with those reported in the US. In general, yields for physical sputtering appear to range downward from 1×10^{-2} for most candidate

materials. Although this does not assure freedom from plasma impurity problems, it makes serious wall erosion by this process improbable.

- . Fluxes to first walls

Data has recently been provided by members of the plasma physics community which give estimates of the energy distribution of fluxes from plasmas to first walls in operating tokamaks and also in proposed beam driven and ignition tokamaks. This data will be of great use in identifying those energy ranges which are most important for surface experiments.

- . Honeycomb walls

Experimental work to provide data for comparison with calculations on the relative yields of planar and honeycomb walls is in progress, and it is expected that an assessment of the actual effectiveness of this concept will be available by the end of the fiscal year. Suppression of impurity influx by a factor of 4 is theoretically predicted.

Attention is turning to two new areas to further reduce impurity introduction. The first is the study of sputtering of charged and neutral particles, with the objective of increasing the fraction of particles which are sputtered in a charged state, thereby permitting their deflection back to the wall by the toroidal field. The second is consideration of surface treatment by ion implantation, coatings, or other means, as a way of producing and sustaining within the exposed surface of an operating tokamak, the composition which is optimum for impurity suppression.

Major Milestones and Funding Summary

Fiscal Years - Millions

Budget: Plasma Materials Interaction	1976	1976T	1977	1978	1979	1980	1981	1982	FY 78-82 Total
Operating	1.63	0.39	2.05	2.8	3.6	4.5	5.0	5.0	20.9
Equipment	0.41	0.08	0.37	0.43	0.5	0.5	0.6	0.6	2.63

Milestones

- . Establish Task Group on Plasma-Materials Interaction..... August 1976
- . Establish preliminary target goals to meet the plasma-materials interaction requirements of commercial fusion power..... March 1977
- . Develop detailed milestones that complement the alloy development program..... May 1977
- . Operate surface diagnostics packages on Alcator and ORMAK..... October 1977
- . Begin surface experiments in ISX..... December 1977
- . Operate Multiple Beam Radiation Facility (MBRF)..... September 1979
- . Complete single beam experiments..... March 1980
- . Begin surface diagnostics in TFTR..... October 1981

3. Special Purpose Materials Development

Objectives and Scope

This technical area covers the development of materials other than first wall/structural materials described previously. Included are the following materials applications:

i) Insulators for superconducting magnets

The lifetime of superconducting magnet insulators is limited due to neutron and gamma radiation damage. Since the properties of insulators deteriorate at fluences lower than those impairing the performance of the superconductor, insulators are generally regarded as limiting the overall magnet performance at this time.

ii) Radiation damage of superconducting magnet wire

The current carrying capacity of superconductors is impaired by neutron irradiation, and performance. Characteristics have to be defined as a function of accumulated damage.

iii) Insulators for electrical and structural applications

The theta pinch first wall is the best example of an insulating requirement for a structural component. Bulk and surface dielectric strength and resistivity requirements have to be met subsequent to each cycle of irradiation and in the presence of high temperatures, chemical attack and variable stresses.

Many other examples of insulator requirements exist, among them those for neutral beams where voltage holding capability is all important, and sputtering and evaporation of electrodes may become problems as neutral beam energy is increased.

iv) Moderator and breeding materials

Several schemes for neutron moderation and breeding have been identified in systems studies. All of them raise questions regarding radiation damage to moderating materials, compatibility, and chemical and mechanical behavior of solid breeding materials.

v) Heat transfer and energy conversion systems

Intermediate heat exchangers and steam generators present traditional problems in structural design, compatibility and long term reliability which need to be addressed within the context of specific fusion systems.

vi) Other applications

Many other materials requirements will become obvious with time and will be addressed as they become identified.

Technical Approach

The approach to solving technical problems in this subprogram varies with the particular problem area. The Task Group on Special Purpose Materials will be asked to address individual areas over the next 12-18 months.

Recent Achievements

The one area that has received attention in the past two years is the development of insulators for structural purposes. The following milestones have been achieved:

- EBR-II irradiations of different ceramics were initiated. The first capsule was removed in January 1976 at a fluence of $2 \times 10^{21} \text{ n/cm}^2$ ($E_n > 0.1 \text{ MeV}$). Two other capsules are scheduled for removal in December of 1976 after irradiation to $2 \times 10^{22} \text{ n/cm}^2$ ($E_n > 0.1 \text{ MeV}$).
- An Insulator Workshop was held at LASL in May of 1976 to assess progress made in the past 18 months and to define the requirements for fusion reactor insulator applications.

Major Milestones and Funding Summary

Budget Special Purpose Materials Development	<u>Fiscal Years - Millions</u>								
	1976	1976T	1977	1978	1979	1980	1981	1982	FY78-82 Total
Operating	1.17	0.26	0.81	1.0	1.2	1.8	2.3	2.8	9.1
Equipment	0.24	0.02	0.12	0.08	0.1	0.2	0.2	0.3	0.88

Milestones:

- . Evaluate superconducting magnet insulator needs and initiate program.....October 1976
- . Evaluate special purpose materials problem areas and develop detailed milestones to meet requirements.....June 1977

4. Damage Analysis and Dosimetry

Objectives and Scope

The objectives of the Damage Analysis and Dosimetry subprogram are to characterize available irradiation test environments and to establish a basis for predicting materials performance under irradiation in a fusion reactor environment. This will be accomplished by materials irradiation data obtained in fission reactors, accelerator based neutron test environments (RTNS, INS, d(Li,n), d(Be,n), etc.) and charged particle irradiations.

The scope of the Damage Analysis and Dosimetry subprogram includes development of the methodology and nuclear data base required for characterization of the reactor test environment. Included are the development of fundamental radiation damage models, the development of methods to account for interactive phenomena in the evaluation of damage structures, the relationship of structure and damage parameters to property changes, and

the application of the above to the prediction of material performance in fusion reactor systems.

Technical Approach

Damage analysis relies on a relatively well established methodology for the fission program which needs to be extended to the fusion environment. Included are calculations, and wherever possible measurements, of damage by high energy neutrons both for displacement and transmutant production. Included also are calculations of pulsed versus steady state effects. Ion irradiations and high energy neutron experiments will be conducted to support the calculational efforts.

Recent Achievements

A precursor to the Radiation Damage Analysis and Fundamental Studies Task Group was convened by DMFE in February of 1976. This group, called the DCTR Radiation Damage Assessment Panel was asked to "evaluate test environments for fusion reactor materials." The preliminary Panel report, published in May 1976, contains an extensive state-of-the-art review of damage analysis, an extensive description of fusion reactor and neutron irradiation test environments, and a series of recommendations on the application of damage analysis principles to the evaluation and utilization of radiation test environments.

Major Milestones and Funding SummaryFiscal Years - Millions

Budget: Damage Analysis and Dosimetry									FY78-82
	1976	1976T	1977	1978	1979	1980	1981	1982	Total
Operating	0.85	0.26	0.61	1.0	2.0	2.2	2.5	2.5	10.2
Equipment	0.18	0.04	0.10	0.03	0.2	0.2	0.3	0.3	1.03

Milestones:

- . Convene DMFE Task Group for Radiation Damage Analysis
and Fundamental Studies..... September 1976
- . Complete initial detailed Program Plan for Damage Analysis..... March 1977
- . Complete BCC Charged Particle Interrelation Program..... July 1977
- . Characterize d(Be,n) and d(Li,n) in support of Radiation
Facilities Development Program..... December 1977
- . Establish intercorrelations among low fluence neutron
irradiation test environments for model materials in
support of Paths A, B and C of the Alloy Development for
Irradiation Performance Task..... 1980
- . Establish intercorrelation at high damage levels for model
materials in a number of irradiation test environments..... 1983

- Establish high fluence damage correlation for engineering alloys in fission reactor and d(Li,n) for Path A and Path B..... 1985

5. Radiation Facilities Development and Operation

Objectives and Scope

The objectives of this subprogram are to define the radiation environment of fusion reactors and to pursue the development of neutron and plasma sources to simulate this environment for materials testing. Since fusion reactors are not now available for testing, high energy neutron and plasma sources are needed to develop materials for commercial fusion power.

Technical Approach

High energy neutron sources are based on the deuterium-tritium (DT) reaction to produce 14 MeV neutrons and on the d(Li,n) and d(Be,n) stripping reactions to produce a broad neutron spectrum of high energy. Two DT neutron sources authorized for construction by Congress are the Rotating Target Neutron Source, RTNS, being built at LLL and the Intense Neutron Source, INS, being built at LASL. The RTNS is designed for 14 MeV neutron fluxes on the order of 2×10^{13} n/cm²-sec at the specimen, while the INS is designed for 14 MeV fluxes of up to 10^{14} n/cm²-sec at the specimen. Proposals for a

$d(\text{Li},n)$ neutron source of much larger volume and higher flux are under evaluation, This source will have a distributed spectrum which has been shown in the past year to be an excellent simulation of the fusion reactor damage spectrum. $D(\text{Be},n)$ sources for specimen irradiations to relatively low fluences exist at several laboratories. Fission reactors are used in the program for testing of nickel-bearing materials because of the two-stage reaction for helium production in mixed fast and thermal reactor spectra. Thus, fission reactors permit simulation of helium/dpa damage accumulation similar to that which occurs in fusion reactors. Unfortunately, this statement is true only for nickel-bearing alloys and high energy neutron sources are needed for all other materials.

The above sources will be used to accumulate neutron radiation data for materials development as well as to contribute to an understanding of damage analysis and extrapolation of fission reactor data to the high energy fusion reactor spectra. The program is currently evaluating the need for a multi-beam facility to simulate the effects of a plasma on the first wall. Materials studies to date have only addressed this problem by evaluating the effects of single neutron or particle

beams on materials surfaces. Multiple beam evaluations including neutrons as well as charged or neutral particles need to be undertaken in materials evaluation and development to more accurately simulate reactor types of plasmas. Although confinement devices such as ISX are necessary steps in the understanding of the plasma-wall interaction, they do not simulate reactor conditions.

All facilities when constructed will be used by DMFE contractors on a priority system to be established by DMFE. The cost of operation of all facilities as well as development costs prior to construction authorization (except for d(Li,n) where the total estimated development is shown), plus the cost of facilities built under MDF Procedures are included in this subprogram.

Recent Achievements .

The RTNS and INS were authorized by Congress for construction in FY 1976. During the third quarter of FY 1976, DMFE convened an ad hoc Neutron Source Proposal Technical Evaluation Panel to evaluate proposals from four ERDA laboratories for a d(Li,n) neutron source. A decision is expected to be made during the transition quarter following FY 1976.

A second Panel on Damage Assessment was convened in February 1976 to evaluate potential radiation environments for simulating fusion reactors. One of the conclusions of this Panel was that "...the transmutant damage parameters of the (d,n) stripping sources more closely match those of the first wall of a fusion reactor than any of the other neutron environments considered".

Major Milestones and Funding SummaryFiscal Years - Millions

Budget: Radiation Facilities Development and Operation	1976	1976T	1977	1978	1979	1980	1981	1982	FY 78-82 Total
<u>Operating Details</u>									
MDF on Multibeam Facility	--	--	--	1.3	0.9	--	--	--	2.2
Multibeam Facility Operation	--	--	--	--	--	0.4	0.4	0.4	1.2
Fission Reactor Operation	--	--	--	0.3	0.6	0.7	0.7	0.7	3.0
D-Be Operation	--	--	--	0.2	0.2	0.2	0.2	0.2	1.0
D-Li Development and Operator Training	--	--	2.35	3.2	2.8	2.4	1.5	1.5	11.4
RTNS Upgrade and Operation	0.50	0.17*	--	0.4	1.8	2.0	2.0	2.0	8.2
INS Upgrade and Operation	0.80	0.18*	--	--	--	--	0.6	2.3	2.9
Miscellaneous	0.53	0.03	0.57	0.1	0.1	0.1	0.1	0.1	0.5
Total Operating	1.83	0.48	2.92	5.4	6.4	5.8	5.5	7.2	30.3
Total Equipment	0.29	0.04	0.30	1.03	1.2	0.7	0.7	0.8	4.43

* Funding and Technical Responsibility Transferred to TPO

Milestones:

- Decision to develop and build high energy neutron sources with fluxes in the 10^{13} - 10^{14} n/cm²-sec range..... 1975 Achieved
- Decision to develop and build a larger volume, higher flux (10^{15} n/cm²-sec) neutron source facility. Select from competing designs..... October 1976
- Decision to build multibeam test facility incorporating DT-plasma components for surface radiation testing..... November 1976
- Operate Rotating Target Neutron Source (RTNS) facility at LLL..... 1978
- Operate Intense Neutron Source (INS) facility at LASL..... 1981

E. Fusion Systems Engineering

The principal objective of Fusion System Engineering is to provide the technical framework for the evaluation, assessment and guidance of the Magnetic Fusion Energy R&D program. Program goals and milestones are established and evaluated on the basis of maximizing the probability of progress success within a minimum practical program cost and with an acceptable level of risk.

The Fusion Systems Engineering program is presently divided into six categories:

Advance Design

Systems Studies

Blanket and Shield Engineering

Tritium Processing and Control

Plasma Systems

Plant Systems

Advance Design provides conceptual design studies for each major D-T burning facility in support of agency requests for authorizations. Systems Studies provide the identification, characterization, and assessment of timing of the technological achievements that must be reached to meet each of the major

program milestones. Blanket and Shield and Tritium Processing and Control tasks provide for reactor subsystem development, and testing to establish the engineering design basis for fusion power systems. Plasma Systems encompass detailed systems analyses of plasma behavior which provides guidance and design criteria for component development programs which are intimately associated with plasma maintenance and control. The Plant Systems area includes work in areas such as Reactor Instrumentation and Control (I&C) and Balance of Plant. An overview of the funding requirements for the next five years for the Fusion Systems Engineering program is shown in Table IV-5.

TABLE IV-5

Fusion Systems Engineering
Budget Summary

		Fiscal Years Millions								FY78-82 Total
		1976	1976A	1977	1978	1979	1980	1981	1982	
Advance Design	Operating:	4.30	.93	3.40	8.00	9.50	10.50	12.00	16.0	56.00
	Equipment:	.03	-	-	-	-	-	-	-	-
Systems Studies	Operating:	2.81	.69	3.50	4.00	4.80	5.55	5.80	6.1	26.25
	Equipment:	.03	-	-	-	-	-	-	-	-
Blanket & Shield Engineering	Operating:	.49	.14	.9	1.80	2.80	4.90	5.00	5.5	20.00
	Equipment:	.02	.03	0.06	.20	0.30	0.50	0.60	0.60	2.20
Tritium Proces- sing & Control	Operating:	0.61	0.15	1.5	2.30	3.27	3.90	4.95	5.2	19.62
	Equipment:	0.12	.03	.54	0.25	0.30	0.50	0.60	0.6	2.25
Plasma Systems	Operating:	.33	0.08	.70	1.10	1.30	2.00	2.60	3.0	10.00
	Equipment:	.01	-	-	0.10	0.10	0.10	0.20	0.2	0.70
Plant Systems	Operating:	.13	0.02	0.30	0.80	1.33	3.15	4.05	4.1	13.43
	Equipment:	.01	-	0.00	.09	0.10	0.30	0.30	0.30	1.09
TOTALS	Operating:	8.67	2.01	10.30	18.00	23.00	30.00	34.40	39.9	145.30
	Equipment:	.22	.06	.6	.64	0.80	1.40	1.70	1.7	6.24

1. Advanced Design

Objectives and Scope

The objective of Advance Design is to identify major fusion facility plant characteristics and performance requirements. This includes design goals and alternatives, which are needed to achieve commercial fusion power in the late 1990's. Advance Design serves to focus the engineering and technology necessary to produce fusion power. Technology requirements are determined in scoping and conceptual design of each major D-T burning facility. The scope includes Tokamak, Mirror and other confinement configurations of interest. These advance designs provide a basis for (1) selecting detailed design alternatives (2) evaluating development and construction costs and schedules and (3) deciding to request authorization to proceed with detailed facility design, construction, and operation. Conceptual design studies provide focus and direction for technology development programs supporting reactor components and systems.

Technical Approach

These objectives are accomplished in four stages. First, scoping studies are performed within the Systems Study category. Systems requirements and available technology are identified to assess the feasibility of proceeding with conceptual design. Second, preliminary conceptual design is performed to develop a "baseline design" where compatible design alternatives are determined and technology requirements are documented. Third, a detailed conceptual design of a facility is completed to

optimize the design, to determine cost and technology requirements and to support requests for congressional authorization. The fourth stage, advanced A-E work (interim funding), is sometimes necessary to determine accurately project cost and schedule prior to Title I construction authorization.

FY-1976 EPR conceptual design efforts continued at ANL, ORNL and GA and included engineering analysis on many plant features of which the following are examples:

- a) basic design alternatives (e.g., divertor vs. non-divertor, circular vs. non-circular cross-sections)
- b) basic design characteristics to mitigate plasma physics uncertainties (e.g., alpha-particle heating, fueling problems, impurity control, etc.)
- c) reactor subsystem design problems (e.g., first wall, blanket and shield, toroidal magnet set, ohmic heating and equilibrium coil systems, energy supply and conversion, reactor maintenance, tritium handling and auxiliary systems).

During FY-77, an evolution of the EPR-1 studies will occur such that preliminary conceptual designs will be oriented toward a prototype experimental power reactor with a main objective of reaching ignition. A separate study will continue on the EPR.

From 1978 through 1981, Advance Design activities will concentrate on the Tokamak devices. Beyond 1981, these efforts will expand to provide for Mirror-PEPR/ITR design and for subsequent devices under alternative concepts.

The devices to be designed conceptually under this category include Prototype Experimental Power Reactors (PEPR) which achieve ignition of the plasma and provide significant plant systems experience; Experimental Power Reactors (EPR) which generate significant net electrical power; Demonstration Reactors (DEMO) which demonstrate the performance of a fusion power system on an electrical grid; and Fusion Experimental Research Facility (FERF) which provide a capability to perform extensive materials and engineering tests in support of major devices.

The pace and direction of the designs are closely coordinated with the total Development and Technology, the Applied Plasma Physics, Confinement Systems, and the Technical Projects Programs.

Recent Notable Achievements

- . The TFTR conceptual design studies by ORNL and PPPL/Westinghouse were completed in FY 1975 and provided the technical basis for the request for authorization to proceed to the Title I phase of the TFTR project.

- . EPR scoping studies were performed at ANL, ORNL, and GA in FY-1975. They serve as the focus for current R&D efforts and have been essential for near term planning of the Development and Technology, Applied Plasma Physics and Confinement Programs.
- . During FY-1975, LASL initiated a study on the Scyllac Fusion Test Reactor. This work continued in FY76. A baseline design is to be documented.

Major Milestones and Funding Summary

Funding Requirements:

	1976	1976A	1977	1978	1979	1980	1981	1982	FY78-82 TOTAL
OPERATING	4.30	.93	3.4	8.0	9.5	10.50	12.0	16.0	56.0
EQUIPMENT	.03	-	-	-	-	-	-	-	-

Major Milestones:

PEPR/ITR (10/85)

Milestone

Date

- . Begin conceptual design 10/76
- . Begin preliminary design and Title I 10/79
- . Begin operation 10/85

Major Device Upgrade

Milestone

Date

- . Identify Key PLT, D-III, TFTR Upgrade Alternatives 10/76
- . Initiate TFTR Upgrade Design 10/81

Mirror (EPR)

Milestone

Date

- . Begin Prel. Conceptual Design 10/86
- . Begin Conceptual Design 10/87

Major Milestones:

Fusion Engineering Research Facility (1991)

<u>Milestone</u>	<u>Date</u>
. Begin detailed conceptual design	10/79
. Initiate Title I	10/82
. Construction Complete	10/89

Experimental Power Reactor (1991)

<u>Milestone</u>	<u>Date</u>
. Begin conceptual design	10/82
. Initiate Title I	10/85
. Construction completed	10/91

2. Systems Studies

Objective and Scope

The objective of systems studies is to provide the basis upon which program managers make choices about future courses of actions within DMFE. The end product of system studies is program action. The scope of this information base that is developed includes three distinct areas: (1) Major Power System Analyses, (2) Component and Subsystem Analyses and (3) Socio-economic/benefit risk analyses. This scope then covers all areas from program cost-benefit analyses to individual component comparative analyses.

Technical Approach

The approach to achieving these objectives is to maintain an iterative procedure of (1) systematically examining program objectives and the alternative strategies for achieving them, (2) identifying key parameters against which program strategies can be evaluated, e.g. cost, technical risk, schedule and (3) developing and comparing the quantitative data for the key parameters.

Presently, systems studies are being performed in five closely related areas:

- . Fusion Reactor Reference Design
- . New Systems/Fusion-Fission Concepts

- . Parametric Studies
- . Econometric Studies
- . Systems Analysis/Technology Assessment

Fusion reactor reference design studies of specific fusion power reactor concepts integrate all elements of fusion reactor design into a self-consistent plant design and define the technological and engineering requirements and limitations and important performance characteristics of each major subsystem.

New Systems and Fusion-fission Concepts studies are performed to determine the extent to which the fusion process can be utilized in forms other than pure fusion reactors. Also included in this area are screening studies of non-mainline fusion confinement methods which may be either a new approach or an old approach previously discarded but having potential based on new findings. Non-mainline approaches, such as shock tubes, laser heated solenoids, and relativistic E-beam heated solenoids are possible candidates for the breeding of fissile fuel and may be studied on a limited basis. Other non-mainline approaches, such as steady state toroidal reactors (bumpy torus and stellarator) and the reverse field Z pinch, if appropriate, also may be studied for both pure fusion and fusion-fission applications.

Parametric studies of fusion systems are performed with computer codes which mathematically describe the operation of each reactor subsystem and the integration of these subsystems into a self-consistent reactor configuration. They will provide analysis of the sensitivity of overall system performance and economics to various technical reactor parameters and thus help to define optimum power systems and provide basis for evaluating promising fusion reactor concepts.

Econometric studies are analyses of a broad nature which help define the role of fusion both for the United States and the world in the context of available alternative energy sources such as fission, fossil, solar and geothermal systems. At present these analyses are based on linear cost/benefit static and dynamic codes at BNL and PNL which prescribe fusion reactor performance, costs and implementation schedules to compete with alternative power sources.

As more data become available from other systems studies (reactor design) and systems analysis (PERT programming), these codes will be modified to provide more refined parametric examination of sensitive independent and dependent variables such as plant capital and operating costs, resource problems, fuel costs and market entry dates.

System Analysis has two elements. One is the production of necessary tools which can be used to accomplish overall system studies objectives. The work at the University of Texas on the Advanced Optimization Code is an example of this. The second area is the one of Application Studies which supports both the New Systems Concepts and the Econometric Studies.

Applications Studies are performed to characterize more clearly the role of fusion power systems in providing benefits in addition to central electric power stations.

Current applications studies focus on Energy Park configurations for fusion and fusion-fission. Materials processing (chemical, agro-industrial, etc.) and synthetic fuel production also are being studied.

Technology assessments have been performed on the effects of impurities on tokamak reactor dynamics and of the engineering feasibility of various combinations of blanket and shield materials. Presently, the focus of these efforts is on defining the requirements for fusion reactor subsystems and assessing the state of technology required to satisfy these requirements.

Recent Notable Achievements

- . Commercial reference reactor designs performed at the University of Wisconsin and PPPL, and provided preliminary data relative to the economic potential of fusion reactors (i.e., plant capital costs and \$/KWH).
- . Preliminary studies completed in FY 1975 for mirror and linear theta-pinch hybrid reactors indicated that these applications of fusion power may be potentially attractive; however additional effort is not warranted at this time.
- . Initial parametric systems analysis codes have been developed for all three magnetic confinement concepts at ANL in FY-1975.
- . Applications studies performed at BNL in FY 1974-1975 have identified a number of non-electric goods that could be produced by fusion reactors. These include synthetic fuels, industrial chemicals, and a variety of primary metals.

Major Milestones and Funding Requirements

Funding Requirements:

	1976	1976A	1977	1978	1979	1980	1981	1982	FY78-82 TOTAL
OPERATING	2.81	.69	3.5	4.0	4.8	5.55	5.8	6.1	26.25
EQUIPMENT	.03	-	-	-	-	-	-	-	-

Major Milestones:

Systems Studies

<u>Milestone</u>	<u>Date</u>
. Initiate Mainline DEMO studies	7/75
. Initiate Tokamak commercial reactor studies (Circular & Doublet) ^{1/} and EPR scoping study	10/77
. Assess Tokamak Commercial Reactor Designs	10/78
. Initiate Alternate Concept commercial reactor designs	10/79
. Initiate SSTR-EBT DEMO design	10/80

Fusion-Fission/New Systems

<u>Milestone</u>	<u>Date</u>
. Initiate TCT Tokamak and Mirror Fusion-Fission scoping/commercial reactor design study	7/75
. Initiation of low Q, non-mainline electric breeder scoping/commercial studies	10/75
. Initiate Steady-State Toroidal Reactor--EBT (SSTR-EBT) scoping/commercial reactor design study	7/75
. Initiate EPR/DEMO fusion-fission design for TCT Tokamak; Mirror; and Low Q, Non-Mainline concepts	9/77
. Evaluate design studies for SSTR-EBT	10/77
. Evaluate TCT Tokamak; Mirror, Linear Theta-Pinch; and Low Q, Non-Mainline fusion fission concepts	10/79

^{1/} Mirror & Theta-Pinch design teams to focus on EPR (Advance Design)

Major Milestones:

Parametric Analysis

<u>Milestone</u>	<u>Date</u>
. Provide parametric codes for Tokamak, Mirror and Theta-Pinch fusion reactors	9/77
. Provide parametric codes for Tokamak, Mirror, Linear Theta-Pinch, and SSTR-EBT fusion-fission reactors and for SSTR-EBT Fusion Reactor	9/78
. Provide Global parametric code	9/80

Econometric Analysis/Systems Analysis/Technology Assessment

<u>Milestone</u>	<u>Date</u>
. Initiate assessment of stainless steel activation problems	7/75
. Initiate economic assessment of mainline fusion-fission energy systems	7/75
. Fusion Fission Technology Assessment	10/77
. Fusion Power Technology Assessment	9/79
. Fusion Technology Assessment	10/77

3. Blanket and Shield Engineering

Objectives and Scope

Blanket and Shield Engineering provides neutronics data, calculational techniques, and benchmark testing in support of pure fusion and fusion/fission reactor blanket designs. Blanket designs are developed to show strengths and weaknesses of various materials combinations and to identify critical development needs. Development programs are established to answer key design related questions and, later in the program, experimental blanket modules are to be fabricated and tested in a fusion reactor environment. This blanket design and testing activity draws upon basic materials property and radiation damage data developed in the DMFE Materials and Radiation Effects program.

Technical Approach

The Neutronic Data Development activity provides data for fusion reactor blanket and shield design. Data assessment is performed as blanket and first wall designs are produced and also through more ordered sensitivity analyses. Measurements and/or nuclear model calculations then are undertaken in response to identified needs. Most cross section measurement needs will be satisfied by programs in the Division of Physical Research. However, the DMFE will maintain a capability to support measurements which are critical to the program and which could not be provided soon enough under the DPR

program. As new measurements become available they will be evaluated (including error files), provided to the ENDF library, processed into forms which can be used in MFE design analysis, and incorporated into the MFE data file. Finally, this activity will provide some support for nuclear data centers so the fusion community has ready access to the latest available data and calculational tools.

The Neutronics Methods Development activity will provide for the development of calculational techniques and codes required for design of CTR blankets and shields. Included will be such items as 1) extending transport theory and Monte Carlo codes to toroidal geometry, 2) improving nuclear data processing codes (Kerma factors, radioactivity, gamma production, gamma interaction, covariance matrices, self shielding factors, etc.), and 3) combining transport and Monte Carlo calculations for efficiently analyzing detailed blanket and shield designs. Development of techniques for sensitivity analysis and calculation of recoil spectra for materials damage studies is also included.

The Neutronics Benchmark activity will support small scale calculational efforts aimed at scoping neutronic problems of particular interest (e.g., the effect of penetrations in MFE blankets). It also will allow limited study of blanket and shield optimization from a neutronics point of view. Results from these studies, aimed at maximizing tritium production, heat generation, shielding effectiveness,

etc., will be provided to those doing Advanced Design and Systems Studies. Benchmark experiments will be performed to gain confidence in nuclear data calculational techniques. The first priority will be testing in support of PEPR or EPR.

The Blanket and Shield Engineering and Methods Development activity will look in detail at specific designs for liquid lithium, molten salt, solid, minimum activity, and fusion-fission blanket designs. The designs will consider: materials compatibility; the impact of pulsed operation on the tritium breeding, the power cycle, and thermal fatigue of the structure; tritium extraction; the effect of coolant and structure materials on magnetic fields; maintenance and replaceability; economics; etc. From these studies will come an assessment of technology needs (heat transfer, thermal hydraulics, structural analysis, thermal energy storage, fatigue data, etc.) to support each of the general blanket concepts as well as a determination of the designs with the highest potential for success. Methods development tasks (thermal hydraulic analysis, structural analysis, and reliability/safety analysis) will be undertaken to satisfy some of these technology needs. Experimental needs will be addressed under Blanket Fabrication and Testing and Coolant Chemistry and Purification tasks, but design of a Blanket and Shield Test Facility will be carried out by this task. Basic materials data

will come from the Fusion Reactor Materials Subelement. Finally, designs of prototypic blanket modules for DEMO and commercial plants will be developed for extensive testing. The blanket engineering activity must look at near term PEPR/ITR needs and must explore all viable concepts until the most promising approach for long range fusion reactor application is found. It is expected that at least two basic concepts will be selected and carried to a point where DEMO plant design decisions are made.

The Blanket Fabrication and Testing activity will respond to the technology needs identified in the above blanket design studies as well as to those identified in specific reactor studies. Included will be testing of liquid metal pumping and heat transfer in high magnetic field, first with NaK or sodium and then possibly with lithium. Molten salt loop experiments may be performed if design studies indicate this to be a viable concept and to the extent that Molten Salt Reactor data are not applicable. Data on high temperature/radiation behavior of solid breeder materials (sintering, creep, swelling, and tritium release) will be obtained. Experimental blanket and shield modules (pure fusion and fusion-fission) will be fabricated and tested to verify manufacturability, thermal hydraulic and structural design adequacy, and maintainability. Finally, blanket and shield modules of differing

design will be tested under near prototypic irradiation conditions in PEPR or FERF/ETR to verify the complete blanket design.

The Coolant Chemistry and Purification tasks will explore means of measuring and controlling impurities in liquid metal, molten salt and helium coolant systems. There will be a close interface with work on tritium extraction from coolant.

Recent Notable Achievements

- . A Blanket and Shield Workshop was held at BNL to investigate fusion reactor design problems
- . "A Comparative Study of the More Promising Combinations of Blanket Materials, Power Conversion Systems, and Tritium Recovery and Containment Systems for Fusion Reactors" was performed and published as an ORNL report (TM-4999)
- . The nuclear data requirements for TFTR have been evaluated and a LASL report published (LA-6118-MS)

. The MFE multigroup library has been issued by RSIC for testing by the MFE neutronics community

. A decision was made to initiate a neutronics mockup experimental program in support of PEPR/ITR.

Major Milestones and Funding Summary

Funding Requirements:

	1976	1976A	1977	1978	1979	1980	1981	1982	FY78-82 TOTAL
OPERATING	.49	.14	.9	1.8	2.8	4.9	5.0	5.5	20.0
EQUIPMENT	.02	.03	.06	.20	.30	.50	.60	.60	2.20

Major Milestones:

Nuclear Data Development

Milestone

Date

- . Complete assessment of TFTR data needs 12/75
- . Multi-group cross-section library for MFE use tested and available for general use 6/76
- . Complete assessment of EPR/FERF/PEPR data needs 1/78
- . EPR/FERF/PEPR neutronics data is available to designer 1/80
- . Complete EPR /DEMO assessment 9/82
- . Neutronic data for EPR /DEMO is available 9/85

Neutronic Methods Development

Milestone

Date

- . Complete update of nuclear heating code 6/77
- . Variational (sensitivity) methods are adapted for parametric and optimization studies 9/78
- . 2D S_n code available for MFE design 9/77
- . 3D Monte Carlo code available for general MFE use 9/79

Major Milestones:

Neutronics Benchmark Calculations and Experiments*

<u>Milestone</u>	<u>Date</u>
. Start calculations to scope specific MFE neutronics problems and plan early experiments	10/76
. Begin blanket and shield benchmark experiments in support of PEPR/ITR	10/77
. Complete initial PEPR/ITR benchmark program	6/79
. Complete engineering mock-up of PEPR/ITR	9/81
. Initiate tritium breeding experiments	10/82

Blanket and Shield Engineering and Methods Development

<u>Milestone</u>	<u>Date</u>
. Complete technological assessment of current pure fusion blanket designs	6/76
. Start methods development to support blanket design	10/76
. Identify detailed needs for structural analysis, fabrication techniques and maintenance technology development (from design efforts)	9/77
. Start preliminary design of Blanket and Shield Test Facility	10/78
. Identify most likely blanket for EPR	9/79
. Initiate Title I construction of Blanket and Shield Test Facility	10/80
. Complete design of test modules for PEPR	9/82

Blanket Fabrication and Testing**

<u>Milestone</u>	<u>Date</u>
. Start tests on pumping and heat transfer of liquid metals in strong magnetic fields	10/77
. Start feature tests on molten salt or He blankets as indicated by design choices	10/77
. Complete initial phase of liquid metal pumping tests	9/79
. Initiate mechanical tests on PEPR first wall and shield	10/80
. Complete feature testing on promising blanket designs	9/82**
. Initiate Testing in Blanket and Shield Facility in support of EPR	10/82

Major Milestones:

Coolant Chemistry and Purification

<u>Milestone</u>	<u>Date</u>
. Start standardization of analytical chemistry methods for liquid lithium	10/77
. Begin to identify and develop techniques for impurity monitoring in other coolants and breeder materials	10/78
. Start loop tests on impurity monitoring and liquid lithium purification	10/79
. Data to support PEPR breeder module design is available	9/81

*The budget allows only for experiments relevant to one machine. Additional funding would be needed for a Mirror PEPR, a FERF or Fusion Fission

**The budget shown in Table 25 does not provide sufficient funds for this task. Also funding is not sufficient for fusion fission.

4. Tritium Processing and Control

Objectives and Scope

Tritium Processing and Control includes (1) the analysis of the projected performance of individual components of tritium handling subsystems; (2) identification of those alternative components and subsystems which require experimental work, component fabrication, pilot plant demonstration, etc., to provide reliable and safe tritium subsystem performance; and (3) research and development necessary to demonstrate all tritium processing and control subsystems required for each major fusion facility. Tritium processing and control is comprised of the following major research areas: tritium fuel cycle, blanket tritium extraction systems, tritium isolation in coolant/energy conversion subsystems, and tritium primary and secondary containment/cleanup systems.

Technical Approach

The near-term program for development of tritium handling technologies for major DT burning facilities is paced primarily by the schedule and technology requirements for PEPR/ITR. A relatively good definition of the PEPR tritium processing and handling system should be provided in the preliminary conceptual design study reports to be prepared by ORNL, ANL and General Atomic Co. at the end of FY 1976. Nearer term facilities such as the Rotating Target Neutron Source and the Princeton TFTR can be designed and

operated by adapting existing technology and experience from the ERDA nuclear weapons program and the commercial light water reactor industry. The LASL Intense Neutron Source may require some development in the areas of cryogenic distillation and cryosorption pumping. This work will be highly relevant to the tritium fuel cycle eventually needed for fusion reactors.

It is worth noting here that a substantial tritium handling technology exists in association with security classified ERDA weapons program activities. ML and PNL are attempting to extract relevant unclassified data from the classified literature to provide better access for DMFE interests. Efforts are also underway to declassify any tritium technology which has direct application to the DMFE Development and Technology program.

The current plan for conduct of the tritium processing and control program may be divided into the following phases:

FY 1974-1975: Comparative surveys and parametric studies have been performed in parallel at several laboratories to identify the more promising tritium handling system configurations for application

to EPR-I or a prototype EPR, with emphasis on identifying and prioritizing the near-term technology development needs.

FY 1976-1977: Conceptual designs for PEPR level tritium handling systems will be conducted. Comparative surveys and assessments will be phased out; being replaced by bench-scale testing and verification of more promising techniques for extracting, purifying, isotopically separating, recycling, storing and containing tritium in PEPR. Development of new methods will be carried out in areas where there are significant technical uncertainties associated with the primary techniques. During this period, "National Centers of Expertise" will be identified (on the basis of quality, pertinence and creativity of work performed for MFE and other organizations) to take the technical lead role in developing selected portions of the tritium handling technology (e.g., the tritium fuel cycle, emergency clean-up systems, etc.) for PEPR and subsequent major DT burning facilities. Classified tritium technology directly applicable to MFE programs will be declassified to the extent practicable.

FY 1978-1982: Test loop and sub-size prototype facilities will be operated to test and qualify tritium handling components and systems for a prototype experimental power reactor. In subsequent

years efforts will be directed toward upgrading tritium technologies to permit safe, reliable operation of the EPR in the early nineteen-nineties.

In association with decisions to construct a FERF/ETR or other PEPR's, laboratories will adapt then-existing technology to the tritium handling requirements.

Recent Notable Achievements

- . ORNL has completed a survey of alternative tritium extraction methods from lithium blankets. The primary purpose of the study was to identify the extraction methods which have technical and economic potential for application to PEPR, EPR-I and subsequent facilities.
- . ANL has completed a preliminary examination of alternative oxide barrier materials and bimetallic metal barrier combinations for inhibition of tritium permeation through reactor heat exchangers and piping.
- . Several laboratories (PPL, ML, ORNL, LASL) have completed designs of the tritium handling systems for FTR's. The relative merits of each design have been compared and it is anticipated that some optimization of TFTR tritium handling systems will result.

- . BNL has completed a preliminary examination of the extractibility of tritium from minimum activity solid blankets containing lithium aluminate, lithium silicate and lithium-aluminum alloys. Early results indicate that acceptable extraction rates can be achieved.
- . ANL has preliminary data which indicates that molten salt extraction offers promise as a method of recovering tritium from liquid lithium.

Major Milestones and Funding Requirements

Funding Requirements:

	1976	1976A	1977	1978	1979	1980	1981	1982	FY78-82 TOTAL
OPERATING	.61	.15	1.5	2.3	3.27	3.9	4.95	5.2	19.62
EQUIPMENT	.12	.03	.54	.25	.3	.5	.60	.60	2.25

Major Milestones:

Fuel Cycle Reprocessing

<u>Milestone</u>	<u>Date</u>
. Initiate design of facility to Prototype EPR fuel cycle and containment/cleanup systems assessment of alternative tritium fuel cycles systems	10/76
. Begin construction of prototype loop facility	7/77
. Initiate operation in facility with hydrogen/deuterium	10/78
. Begin operation of facility with tritium	10/79
. Deliver technology for tritium systems in the PEPR	10/80
. Begin testing optimized components for later D-T reactors	10/80

Blanket/Coolant Extraction

<u>Milestone</u>	<u>Date</u>
. Initiate design of bench scale lithium loop for tritium extraction tests	1/76
. Complete construction of extraction loop	9/77
. Initiate operation of loop with flowing salt and advanced extraction systems	9/78
. Demonstrate bench scale feasibility of extraction from solid breeding materials and molten salts	9/78
. Initiate design of prototype extraction loop for most promising breeding material	7/79
. Begin operation of some systems in the extraction loop	10/81
. Provide technology for EPR tritium extraction systems	9/84

Major Milestones:

Routine/Accident Containment & Cleanup System Design

<u>Milestone</u>	<u>Date</u>
. Initiate experimental tests of candidate barrier systems for tritium handling systems which must operate at elevated temperatures	1/75
. Begin construction of prototype clean up system test facility (in conjunction with fuel cycle loop facility)	7/77
. Begin fabrication of a subsize model low permeation heat exchanger	10/77
. Complete testing and demonstration of alternatives for safe reliable tritium containment and cleanup systems applicable to PEPR/ITR	10/80
. Identify EPR tritium containment/cleanup system technology development requirements, initiate requisite work to upgrade technology developed for PEPR	10/80
. Begin testing of subscale low permeation heat exchanger	1/79

5. Plasma Systems

Objectives and Scope

Plasma Systems is responsible for the analysis of systems which will be necessary to create and sustain a D-T plasma to significant burn-up. Experimental and theoretical data on plasma behavior is developed within the Applied Plasma Physics and Confinement Systems Programs of DMFE. Data on the behavior of materials in a reactor plasma environment (e.g. swelling, sputtering, embrittlement) is developed by the Fusion Reactor Materials subelement to allow determination of the effects of reactor first walls on plasma performance. By analyzing plasma systems in greater detail and over a wider range of parameter space, than possible in reference designs, this category serves as a focal point for coupling materials and plasma physics research data to the design of fusion reactor plasma maintenance systems. The purpose is to define reactor subsystem interface requirements and provide design criteria for Development and Technology Programs and to formally identify basic and experimental research needs to the Applied Plasma Physics and Confinement Systems Programs.

Technical Approach

Primary emphasis within plasma systems is directed towards providing information necessary for the design and proper operation of the PEPR and EPR. Analysis of confinement concepts considered highly

likely for use as FERFs will be conducted as appropriate. In each of the task areas, all confinement concepts require substantial analysis and development; however, at this point in time, alternate confinement concepts have not progressed to the stage where separable engineering design of reactor plasma maintenance systems would be warranted.

At present the critical areas of fusion plasma operation roughly overlap as follows: 1) Start-Up/Shut-Down, 2) Burn Cycle Dynamics, 3) Fueling/Pumping/Impurity Control, and 4) Reactor Plasma Simulation.

Plasma Start-Up/Shut-Down Systems

DMFE Confinement Systems and Applied Plasma Physics programs will provide much information concerning this task. As the plasma start-up/shut-down requirements are determined, D&T will assume major responsibility to oversee the engineering design of poloidal field coils, related power supplies, instrumentation and control and other start-up/shut-down systems. Questions concerning reactor diagnostics for plasma control during start-up/shut-down and steady state also must be answered and Applied Plasma Physics is sponsoring work in this area to identify long range research needs. This

area will be explored to determine a proper sequence of systems analysis and engineering development.

Burn Cycle Dynamics

Efforts in this area will be directed at establishing design criteria for plasma support systems such as neutral beam, RF and ohmic heating, gas blanket and pellet fueling, and first walls as a function of varying reactor plasma performance requirements. Plasma codes will be used to determine the overall plasma operating cycle, in detail, for devices such as PEPR, EPR-I and DEMO.

Fueling/Pumping/Impurity Control

Efforts in this area will be directed at establishing interface requirements among the three systems. At present it is expected that the plasma in PEPR may have to be replaced every few seconds. Three possible methods of supplying fuel to the plasma core have been identified: Neutral particles from a gas blanket, neutral beams and solid DT pellets. Neutral gas blankets are proposed as impurity control protection methods for all three confinement concepts and as a fueling method for tokamaks; however, charge exchange losses for neutral beam driven systems may be excessive with the use of a gas blanket concept. Divertors, proposed for impurity control in tokamaks, would require different pumping and fueling schemes than for gas blankets and low Z or high Z -low sputtering liners. In

addition, determining an accurate description of the total charged particle, neutron and radiation fluxes present at first wall surfaces for these and other schemes will be necessary to guide the materials development program for first wall liners in the proper directions.

Reactor Plasma Simulation

The PEPR and the EPR, although still experimental facilities, will require systems and engineering expertise necessary to operate any device of this magnitude. Fission reactor operators use reactor simulation computer codes to gain some insight into expected design performance characteristics and to train reactor operators. DMFE may develop a control simulator under the Plant Systems I&C category for the same purposes. Plasma simulation codes have been developed within the DMFE program. Under Plasma Systems, such codes will be modified and further developed to contribute to the development of a software package for control panel simulators and reactor instrumentation and control systems.

Notable Recent Achievements

- . Preliminary versions of plasma simulation codes have been used in the ANL, GA and ORNL EPR scoping studies to provide estimates of heating power required for start-up and estimates of resulting fusion power production.

- . The University of Wisconsin has developed a detailed 1-D plasma code for use in the UWMAK design studies.
- . The University of Illinois has compiled a list of cross section and reaction rate parameters for deuterium-tritium and advanced fuel fusion reactions.

Major Milestones and Funding Summary

Funding Requirements:

	1976	1976A	1977	1978	1979	1980	1981	1982	FY78-82 TOTAL
OPERATING	.33	.08	.7	1.10	1.30	2.00	2.60	3.00	10.0
EQUIPMENT	.01	-	-	.1	.1	.10	.2	.2	.7

Major Milestones:

Plasma Start-Up/Shut-Down

<u>Milestone</u>	<u>Date</u>
. Complete assessment of plasma diagnostics which are operable in reactor development	9/77
. Complete assessment of plasma control techniques	9/77
. Complete conceptual design on reactor plasma start-up/shut-down system	9/79

Burn Cycle Dynamics

<u>Milestone</u>	<u>Date</u>
. Complete estimate of start-up/heating requirements for PEPR	9/77
. Verify TCT calculations via D- ³ He experiments on PLT. Outline possible D- ³ He experiments for TFTR	12/77
. Complete analysis of gas blanket and neutral beam heating phenomena via TFTR experiments	9/82

Major Milestones:

Fueling/Pumping/Impurity Control

<u>Milestone</u>	<u>Date</u>
. Complete assessment of gas blanket experiments on PLT	9/77
. Complete assessment of proposed methods of impurity control/wall protection and pumping for PEPR	12/77
. Complete assessment of pellet fueling experiment on PLT	9/77
. Complete assessment of pellet fueling experiment on Doublet-III	9/79
. Complete assessment of gas blanket experiment on TFTR	9/82
. Complete assessment of prototype (EPR) PEPR fueling test on TFTR	12/82

Reactor Plasma Simulation

<u>Milestone</u>	<u>Date</u>
. Complete reactor simulation code sub-module capable of modeling plasma behavior in a real time simulator	9/82

6. Plant Systems

Scope and Objectives

Plant Systems is a new activity which addresses problems of a general systems nature which would not naturally fall within the other five categories of Fusion Systems Engineering. Presently identified tasks are in the areas of 1) reactor and plant instrumentation control and diagnostic systems, 2) fusion reactor and plant radiation engineering requirements, 3) system and component reliability, and 4) balance of plant features that will be unique to fusion power plants. Radiation engineering deals with those operation and maintenance considerations which result from the neutron and gamma environment of a fusion reactor.

Technical Approach

Two areas in this area are currently active. An assessment of the instrumentation and control requirements of fusion devices from the present generation proof of principal experiments, through an experimental power reactor is underway. Problems which will have to be solved for fusion reactors are being identified and ways of finding and testing solutions on present generation experiments are being explored.

The instrumentation and control system has a central role in fusion power plants. This role includes plant supervision functions for all subsystem elements providing for power generation and power conversion. It must have the capability for the control of all energy flows which have the potential for disturbing overall system operation; it therefore includes fault diagnostic capabilities for detection and identification of system failures and disturbances and means of reacting to them safely while maximizing plant operational availability.

The pulsed power characteristic and the interactive nature of the controlled plasma and energy conversion systems of a fusion device or power plant creates an inherently difficult control problem. Consequently, the control requirements are extremely complex. For these reasons we anticipate the need for a test bed which simulates the complex interactions of all nuclear island and plant systems with the control system. This could be an experimental device or a system simulator and will rely heavily on plasma simulation work carried out within Plasma Systems as well as control and diagnostic tasks associated with each major subsystem.

The other active area is relative to the maintenance requirements of fusion reactors. Initially, these radiation engineering studies will be performed to identify feasible approaches to tokamak

maintenance. These evaluations will be integrated with the EPR/PEPR design efforts. Later in the program focus will turn to a comparative evaluation of radiation engineering aspects of all confinement concepts. Specific design/development efforts will be undertaken after the best approaches have been defined.

The other areas of Plant Systems will be approached in a manner similar to I&C and radiation engineering. Independent studies will be performed to assess in detail what has to be done. Specific R&D tasks will then be funded. All of these activities will be carried out in close cooperation with reactor designs funded by Advance Design and Systems Studies.

Recent Notable Achievements

- . An assessment of the PLT I&C systems has been completed by C. S. Draper Laboratory, Inc.
- . The issue of plasma feedback control on tokamaks, especially during abort situations, has been identified as a significant problem for reactors of TFTR size or larger.

Major Milestones and Funding Summary

Funding Requirements:

	1976	1976A	1977	1978	1979	1980	1981	1982	FY78-82 TOTAL
OPERATING	.13	.02	.3	.8	1.33	3.15	4.05	4.10	13.43
EQUIPMENT	.01	-	-	.09	.10	.30	.30	.30	1.09

Major Milestones:

Plant Systems

<u>Milestone</u>	<u>Date</u>
. Initiate study on advanced instrumentation and control system	10/75
. Initiate study on Tokamak maintenance problems	10/76
. Complete study on advanced I&C, Initiate detailed subsystem design	10/77
. Initiate assessment of additional required development for fusion power plant systems; e.g., B.O.P., Steam generator, support systems	10/77
. Complete initial study of Tokamak maintenance	9/77
. Initiate study of reliability program for fusion reactors	10/77
. Complete assessment of required BOP development for fusion power plant systems	7/78
. Initiate development work for fusion power plant systems; e.g., steam generators, valves, instrumentation, control and fault diagnostic systems	10/78
. Complete tests of PEPR reactor and plant control scenarios on TFTR or system simulator as a basis for the PEPR instrumentation and control design verification	9/83

F. Environment and Safety

The ultimate acceptability of fusion reactors as a major national energy source will depend, in part, on the safety and the environmental impact of their operation. The objective of the Environment and Safety Program is to assure that the development and ultimate operation of fusion power reactors is accomplished with minimum adverse effect on the environment and with maximum safety for both the public and for ERDA and ERDA contractor personnel and property. The approach of the program is to identify and evaluate all potential hazards related to operation of fusion power reactors, to develop necessary engineered controls and safeguards to counteract such hazards, to incorporate appropriate safety features into the design of each fusion facility, and to perform and document systematic and assessment analysis of the safety and environmental effects of each fusion facility. The program is currently divided into three major categories: 1) Environmental Assessment, 2) Facility Safety Analysis, and 3) Fusion Reactor Safety Research. An overview of the funding requirements for the next five years for the Environment and Safety subelement is shown in Table IV-6 .

TABLE IV-6

Environment and Safety Budget Summary

		Fiscal Years Millions							
		1976	1976A	1977	1978	1979	1980	1981	1982
		FY78-82 Total							
Environmental Assessment	Operating:	0.45	0.11	0.25	0.3	0.7	1.0	0.6	0.6
	Equipment:								
Facility Safety Analysis	Operating:			0.1	0.1	0.3	0.5	0.6	0.9
	Equipment:								
Fusion Reactor Safety Research	Operating:			0.6	0.6	1.0	1.5	2.2	2.4
	Equipment:				0.12	0.2	0.3	0.3	0.4
TOTALS	Operating:	0.45	0.11	0.95	1.0	2.0	3.0	3.4	3.9
	Equipment:				0.12	0.2	0.3	0.3	0.4

1. Environmental Assessment

Formal analysis of environmental impact is required for all major federal actions, including broadly based R&D programs as well as specific projects. The magnetic fusion program must assure that these requirements are properly met.

Objective and Scope

The Environmental Assessment program assures that environmental considerations are factored into decisions to construct and operate major fusion facilities which could have significant environmental impacts, and assures that the environmental impact of the fusion power R&D program as a whole is evaluated as input to ERDA and congressional decisions on long term program support.

Technical Approach

An Environmental Statement (ES) will be published for each major facility and an ES for the overall fusion power R&D program will be prepared at such time as adequate information is available to meaningfully examine the environmental implications of a national fusion power program.

Recent Achievements

PNL is completing a comprehensive environmental analysis of the fusion R&D program, expected to be published early in FY 77. Scheduled for publication in FY 76A are a series of topical reports prepared by PNL as a result of the work done in developing the environmental analysis. These reports, which deal with specific aspects of the potential fusion program environmental impacts, will include identification of areas where further research is needed. PNL also published a report delineating the information requirements pre-requisite to preparation of magnetic fusion environmental impact statements.

An Environmental Statement was prepared by PPPL/Westinghouse/ERDA for the Princeton TFTR and was issued in final form in July 1975. LASL/ERDA prepared an Environmental Statement for the Intense Neutron Source Facility, which was issued in final form in July 1976.

Major Milestones and Budget Summary

Budget Summary:

	1976	1976A	1977	1978	1979	1980	1981	1982	FY78-82 TOTAL
OPERATING EQUIPMENT	0.45	0.11	0.25	0.3	0.7	1.0	0.6	0.6	3.2

Milestones

Date

- . Approve Environmental Statement for TFTR 6/75
- . Review Environmental Analysis for Fusion R&D Program 10/76
- . Approve Environmental Statement for INS 7/76
- . Approve Environmental Statement for PEPR 1979
- . Approve fusion power R&D program Environmental Statement 1980

2. Facility Safety Analysis

The successful development of fusion power reactors, as well as their ultimate licensability and public acceptance, require documentation of formal safety analyses for each fusion reactor facility.

Objective and Scope

The objective of the Facility Safety Analysis program is to develop an appropriate methodology for fusion reactor safety analyses. Such analyses should assess plant safety in the early design stages, and document incorporation of plant safety features into facility design.

Technical Approach

For each major fusion facility, a Preliminary Safety Analysis Report will be prepared prior to construction and a Final Safety Analysis Report will be prepared prior to operation. An appropriate and consistent safety analysis formalism for fusion reactors will be developed.

Recent Achievements

This is a new program, with initial funding planned for FY 77.

Major Milestones and Budget Summary

Budget Summary:

	1976	1976A	1977	1978	1979	1980	1981	1982	FY78-82 TOTAL
OPERATING			0.1	0.1	0.3	0.5	0.6	0.9	2.4
EQUIPMENT									

Milestones:

	<u>Date</u>
. Approve PSAR for TFTR	1977
. Approve PSAR for INS	1978
. Draft Fusion Safety Analysis Definition Document	1978
. Final Fusion Safety Analysis Definition Document	1979
. Approve FSAR for INS	1980
. Approve PSAR for PEPR	1981
. Approve FSAR for TFTR	1981
. Approve FSAR for PEPR	1985

3. Fusion Reactor Safety Research

In order to develop safe, reliable and publically acceptably fusion power reactors, identification, evaluation and control of all potential hazards associated with their operation is required.

Objective and Scope

The objectives of Fusion Reactor Safety Research are to identify and characterize the accident risks of fusion reactors and to develop the engineered safeguards necessary to provide for safe construction and operation. Examples of areas to be examined include the following: loss of coolant accidents; tritium release accidents; natural phenomena such as earthquakes, tornado and floods; magnet safety; remote maintenance and handling; and waste disposal.

Technical Approach

Initially, emphasis will be placed on the identification of research needs to fully identify the hazards which may be associated with fusion reactor operation. These hazards will then be evaluated and, where indicated, development of required engineered controls or safety features will be undertaken. The program will strive to provide timely input to the design of each major fusion facility, keyed to the particular hazard and environmental impact potential of each facility.

The Division of Biomedical and Environmental Research (BER) has agency responsibility for environmental, biological, and medical research in support of developing energy technologies. The Division of Safety, Standards and Compliance (SSC) is responsible for providing safety guidelines and standards for ERDA facilities. These two divisions will be sponsoring work in support of the fusion safety research program; possible examples are listed below:

1. Evaluation of the biological effects of magnetic fields (BER)
2. Metabolic and environmental behavior of tritium and neutron activation products produced in fusion reactors (BER)
3. Genetic effects of bound tritium (BER)
4. Applied health physics need for fusion reactors (instrumentation, personnel protection, etc.) (BER)
5. Lithium fire safety criteria (SSC)
6. Personnel protection criteria for magnetic and electrical energy storage and transfer system (SSC)

Recent Achievements

This is a new program, with initial funding planned for FY 77.

Major Milestones and Budget Summary

Budget Summary:

	1976	1976A	1977	1978	1979	1980	1981	1982	FY78-82 TOTAL
OPERATING			0.6	0.6	1.0	1.5	2.2	2.4	7.7
EQUIPMENT				0.12	0.2	0.3	0.3	0.4	1.32

Milestones

Date

- . Development of a safety research program plan 1978
- . Development and maintenance of component and system failure rate data files Continuing
- . Safety research to define fusion reactor potential risks Continuing
- . Proof-testing of integrated safety systems (e.g., containment/cleanup systems) Continuing

V. APPLIED PLASMA PHYSICS

A. Introduction

The Applied Plasma Physics Program seeks the body of knowledge that predicts the behavior of fusion plasma confinement experiments and the operating characteristics of fusion power reactors. The program management is composed of three branches: Fusion Plasma Theory, which manages all of the Magnetic Fusion Energy Division's theoretical activities, including its computational component; Computer Services and Technology, with responsibility for the National MFE Computer Center with its associated User Service Centers and Data Communications Network; and Experimental Plasma Research, which supports a broad spectrum of experiments to attack problems related to the production and confinement properties of fusion plasma.

The Applied Plasma Physics Program's theoretical studies have had a continuing impact on fusion research since the early days of primitive plasma confinement experiments. Theory explained the gross instabilities that plagued the early experiments, and it has provided the guidance to eliminate these instabilities. It continues to provide the basis for understanding plasma behavior in the present generation of magnetic confinement experiments. Plasma theory has now matured to the point where it can be used to explain or predict many features of experimental plasmas.

For example, the nonlinear theory of loss cone instabilities in velocity space was recently able to explain the high temperatures and long energy confinement times achieved on 2XII. Stability studies on the Doublet III design led to significant changes in the shape of the chamber of that device.

Although the physics of magnetic confinement can still be only approximately described by abstract and sometimes inadequate models, large scale computational efforts have provided quantitative predictions of plasma properties such as equilibrium stability and energy transport through the use of 1- and 2-D computer codes. Of crucial importance in this effort are analytical models on which these codes are built. Large scale digital computers will play a particularly cost effective role in the design of devices. They will be used to simulate specific characteristics of plasma confinement experiments and fusion power reactors, and eventually they will make possible the simulation of proposed systems before actual construction.

The Applied Plasma Physics Program's experimental activities have contributed significantly to overall fusion research progress in the past. Specialized plasma experiments, such as Q-machines and multipoles, have been used to test and verify features of plasma theory. Many of the instruments to measure the properties of plasmas in magnetic confinement systems experiments were conceived, designed, tested, and perfected in conjunction with some of the special purpose experiments in the Applied Plasma Physics Program. In addition, important advances have been made in plasma production and heating by control of low and high level plasma turbulence, by neutral beam injection, and by relativistic electron beams.

In the future, the experimental component of the Applied Plasma Physics Program will provide continuing research into novel methods of plasma confinement and heating, improved instrumentation, detailed data on relevant atomic and molecular processes, and finally, critical tests of the validity and applicability

of evolving plasma theory. A dedicated experimental plasma research facility (referred to as a Fusion Plasma Research Facility - FPRF hereafter) consisting of a high duty-cycle, medium scale, research-oriented confinement device capable of producing plasmas with thermonuclear or near thermonuclear parameters. This medium-scale confinement device can provide a logical intermediate step between the small plasma devices available in many research laboratories (university, industry, DMFE, other government agency) and the large confinement experiments. With such a device available to experimenters from all sectors of the program, ideas could be explored initially on small laboratory plasma devices; they would then be tested on FPRF and then they could be transferred directly to large confinement systems.

Computer Services and Technology provides computing support for the entire fusion program. Among its functions are systems and software support at the National Computer Center. Computer networking ties the major components of the fusion program into the central computing facility. Specialized computers are being developed to provide the most cost-effective computing for the large codes required by the program.

B. Problem Areas

1. Fusion Plasma Theory

The Fusion Plasma Theory Branch provides the theoretical support for all of the Magnetic Fusion Energy Program including its computational component. The theoretical and computational studies span the following major problem areas:

- Plasma Properties
- Plasma Production and Heating
- Atomic, Molecular and Nuclear Physics
- Exploratory Concepts
- Computer Applications

Plasma Properties - Theory

This activity concentrates on theoretical studies of plasmas in various magnetic field configurations relevant to fusion in order to understand what plasma equilibria are possible and which of the equilibria are stable. The situations for which there is a stable plasma equilibrium must then be analyzed to determine the rate at which plasma diffuses across the magnetic field and is lost to the wall and the rate at which energy is radiated from the system. Such analysis is based on the knowledge of temperature, density, impurity concentration and particle and energy transport properties of the plasma and involves the use of abstract mathematical formalisms, and the solution of nonlinear equations. Excellent progress has been made in developing the body of knowledge needed to understand and predict the behavior of fusion plasmas in confinement systems, and there are effective theoretical models that explain and predict some plasma phenomena. There are many areas, however, in which additional intensive theoretical work is now needed to better interpret and understand the results of present and future generation confinement experiments. For example, one of these areas is the development of theoretical models that would be

able to predict the onset of a disruptive instability in tokamaks. Such a development would lead to an understanding of how to control and reduce the effect of this instability and would permit longer confinement times. Another area is the development of theoretical models which delineate effects of electromagnetic instabilities in mirrors. Such studies would indicate paths to maximum allowable betas. Another area that must be understood is the transport of impurities in a plasma since the temperature of a plasma can significantly be reduced by line radiation from impurities. An area that is important in large experiments is that of understanding the stability of trapped ions in the plasma and consequently, the stability and diffusion of the plasma. Also, increasingly important is the need to develop models and equations for "burning" plasma, i.e., plasmas of deuterium and tritium mixtures undergoing thermonuclear reactions. This is a difficult theoretical task which in the past has not been of primary importance. These theoretical studies are at the heart of the MFE program inasmuch as they provide some of the data that fills the "handbook" on plasma properties needed to design fusion reactors. The growth of this activity is keyed closely to the growth of the experimental part of the program, which depends on the availability of adequate theories for the interpretation of results and for guidance for future experiments. Beginning in FY 1979 there will be a gradual transition from emphasis on confinement related theoretical tasks to ones that are development and technology oriented. This emphasis will continue to grow in favor of the fusion reactor type theories and calculations. Theoretical studies of this nature that will be important to MFE include feedback and dynamic stabilization of plasmas in fusion reactors and studies of plasma interacting with external circuits to recover energy.

Plasma Production and Heating - Theory

Once a suitable and stable plasma equilibrium has been established in a given magnetic field configuration, the next important problem is heating that plasma to thermonuclear temperatures without increasing its diffusion rate, introducing major instabilities, or seriously changing the equilibrium conditions. While there are many methods by which this can be done, most involve nonlinear plasma processes or turbulence; and thus, they are difficult to study mathematically. As a result, in the past the majority of studies in this activity were experimental. However, with the development of more realistic computer codes that can model velocity distribution of heated plasmas, transport of energy and particles in toroidal geometries, as well as some of the effects of atomic and molecular physics on energy confinement, theoretical plasma production and heating efforts are taking on increasing importance. Hybrid particle fluid models have been quite successful in reproducing the dynamics, the density and the temperature profiles of implosion heated plasmas. Special emphasis is given to models that describe the penetration of neutral beams into plasmas with varying geometries in the presence of high-Z impurities and the effect of field ripple on penetration. Studies in atomic and molecular physics are being initiated to determine energy deposition profiles for neutral beams. In the area of RF heating, studies include effects of microinstabilities and trapped particles on penetration and energy deposition by waves.

Plasma production and heating in the presence of runaway conditions in ORMAK and the slide-away conditions in Alcator, as well as the formation of relativistic electron beams in EBT is the subject of intense theoretical study.

Atomic, Molecular and Nuclear Physics - Theory

The theoretical part of the Atomic, Molecular and Nuclear category is directed at obtaining spectroscopic and cross section (effective size) data for impurity ions in tokamak discharges. Impurities such as carbon, oxygen, nitrogen, chromium, iron, molybdenum, nickel, gold and tungsten become partially or highly ionized and may seriously alter the energy balance in hot plasmas. Charge exchange, collisional ionization, and dielectronic and radiative recombination determine the radiant energy lost from the plasma. Too few data on cross sections, rates and line positions are available for these processes. The theoretical program is closely coordinated with the experimental program so that the total effort can be made more effective.

Exploratory Concepts - Theory

The theoretical component of the exploratory concepts category is directed toward developing models to understand the basic physics of new reactor concepts. Exploratory concepts such as EBT, Tormac, Surmac, high-beta tokamaks, reverse field pinches, ion rings, etc. offer the potential of more economical or compact reactors, or may lead to fusion in a shorter time than mainline schemes. Simple theoretical models are essential at the initial stage of an exploratory concept to guide the design and operation

of the first experiments. More sophisticated models permit greater scale steps between successive generations of devices, thereby accelerating the development of the exploratory concept and reducing the overall cost.

Computer Applications - Theory

The use of computers is essential to model the complex environment of a confinement experiment. Analytical theory supplies a basic understanding of individual phenomena, but the integration of many effects for detailed comparison with experiment requires computer codes. Codes are also essential for the detailed design of individual experiments. For example, equilibrium and stability analysis of Doublet III led to a major change in the design of the shape of the vacuum chamber to optimize the effect of the field coils used to shape the plasma.

In fusion reactor studies, computer models provide quantitative predictions on such features of reactors as the dynamics of the burn cycle, alpha particle transport and wall loading.

Computer models have now evolved to the point where two-dimensional models can predict plasma behavior in noncircular geometries. Three-dimensional codes have been developed and successfully applied to inherently three-dimensional problems, such as the equilibrium and stability of toroidal theta pinches. However, because of the need for large storage and long running time requirements, these codes have not been applied to an extensive range of problems.

As computer capabilities increase and as analytic models on which the codes are based undergo iterative refinement through computer usage, three-dimensional codes will provide valuable analysis of confinement experiments.

2. Experimental Plasma Research

The Experimental Plasma Research Branch provides a broad spectrum of experimental data and new experimental techniques which span the following major problem areas:

- Plasma Properties
- Plasma Production and Heating
- Measurements and Instrumentation
- Atomic, Molecular and Nuclear Physics
- Fusion Plasma Research Facility
- Exploratory Concepts

Plasma Properties - Experimental

Research on plasma properties seeks to extend the body of scientific knowledge of the equilibrium, stability and transport of magnetically confined plasmas required to interpret present confinement experiments and to design future large-scale experiments. A particular goal of these experiments is to isolate, when possible, a single phenomena to provide a decisive test of a proposed theoretical model, or to prove a scaling law derived from theory or computation. In some cases the experimental studies are

pursued on small special purpose experimental devices, while in others fairly sizable devices are used that provide magnetic geometries similar to those in mainline confinement devices. Some of the principal problem areas include transport of particles and energy across a magnetic field, development of new techniques for attaining clean plasmas, divertor simulation, end loss in linear systems, and techniques to attain higher beta for toroidal configurations. Experimental measurement of these plasma properties will ensure better interpretation of the PLT and PDX data and provide design information for TFTR and EPR.

Plasma Production and Heating - Experimental

The goal of the plasma production and heating program is to provide an understanding of the various possible plasma production and heating methods in such detail that a rationale choice between competing alternatives in the next generation confinement experiments and in reactor regimes will be possible. Meeting this goal will require a balance of theoretical studies including computer simulation, experimental research on small special purpose devices, as well as experiments on intermediate and large scale confinement devices. Experimental studies are aimed at testing methods of producing plasmas and heating them to thermonuclear temperatures. More specifically, alternate methods for producing or heating plasmas in present confinement devices are explored. Also, detailed studies of energy coupling techniques and absorption mechanisms are pursued in an attempt to improve heating efficiencies of present techniques. Some examples of areas of investigation in this category include RF heating, shock heating, and new or improved positive and negative ion sources for neutral beam systems.

Measurements and Instrumentation - Experimental

This area of research is aimed at providing measurement techniques required to characterize the physical properties of a thermonuclear plasma. New and improved techniques are developed to measure plasma parameters with special emphasis upon providing accurate space and time resolved measurements. In addition, efforts on improved data handling systems and standardization of measurement techniques are pursued. The Fusion Plasma Research Facility (FPRF) would provide a reproducible plasma of known conditions that would be particularly useful for testing new exploratory diagnostic techniques. It would have a complete set of present day, standard diagnostics. Thus, results from any new techniques could be compared directly with the standard measurements, and it would provide an environment reasonably similar to a large confinement experiment so that a successful new diagnostic could be transferred almost directly to a large experiment.

Progress in understanding the characteristics of real plasmas is limited by the effectiveness of the instrumentation used on confinement experiments. Plasma measurements provide the essential link between theoretical predictions and the experiments. Methods to measure ion temperature, plasma current, poloidal magnetic field, neutral particle density and impurity densities are particularly needed.

Atomic, Molecular and Nuclear Physics - Experimental

This program provides atomic and molecular data for analysis of plasma heating and cooling mechanisms, plasma diagnostics and neutral beam injection systems. Most of the program is directed at atomic data of highly ionized atoms, especially heavy element impurities. Line radiation of high-Z impurities, collisional interference with neutral beam heating, and collisional cooling of hot plasma ions are impurity effects that seriously alter the total energy balance in a hot plasma. Atomic data that is required includes spectroscopic data (wavelengths, energy levels, transition probabilities) and effective sizes (cross sections) for bremsstrahlung, radiative and dielectronic recombination, collisional excitation and ionization, and collisional charge transfer.

Molecular and atomic data are required for understanding and design of negative ion sources. Negative ions are the initial element in future high energy neutral beam injection systems. Cross sections are largely unknown for formation and destruction of negative deuterium ions by charge exchange and dissociative collisions with deuterium atoms and molecules. Collisional formation on surfaces is an important process whose dynamics are largely unknown. Cross sections for these mechanisms are required to conceive, design and optimize ion sources.

Nuclear data is required for charged particle nuclear reactions and neutron interactions for evaluation of nuclear heating of auxiliary systems, radiation damage, tritium breeding, shielding and dosimetry. Many of the cross sections for materials of interest in a fusion reactor are unknown. The present program is small but must increase as neutron production increases in fusion experiments and as we approach more detailed engineering design of fusion reactors.

Fusion Plasma Research Facility - FPRF

The fusion program is concentrating most of its effort in relatively large experimental facilities, along with the necessary supporting systems, to increase plasma temperature, confinement time and density. There are in addition, however, several major problem areas where research and development are necessary to continue progress in understanding and improving the large experiments. The areas of impurity data, new and improved local diagnostic techniques and alternative heating schemes are particularly important subjects that require regular access to medium-size state-of-the-art fusion experiments. The FPRF is intended to serve this need by providing a well characterized plasma with many diagnostic viewing ports. This facility would be available to the whole scientific community on an application and approval basis.

Exploratory Concepts - Experimental

In the exploratory concepts category, promising alternatives to the present mainline approaches to fusion power are tested and evaluated. While the present mainline approaches appear promising, a new approach

may lead to fusion power in a shorter time or it may lead to a more compact and economical reactor. Where possible, application of new technology advances are applied to fusion problems. Some of the activities in this area include investigation of toroidal cusp confinement (Tormac), the CO₂ laser heated solenoid, electrostatic confinement, liner flux compression and the use of charged particle beams for plasma heating and magnetic field modification.

3. Computer Services and Technology

As the Network approached stable service, attention has focused on the computer requirements for the next few years. The very rapid saturation of the first CDC 7600 occurred despite the problems of converting codes from other computers and some delay in operational status for the Network.

Plans for FY 1977 called for the transfer of a second CDC 7600 mainframe from another ERDA site, and the budget provides for purchase of the necessary peripherals. This will add much needed capability, but will bring the National Magnetic Fusion Energy Computer Center (NMFECC) capacity only to the initial level recommended in WASH-1296. Earlier projections showed a requirement for three Class IV computers in FY 1976.

To move toward the capability that is needed in both quantitative and qualitative senses, Class VI computers are essential. For realistic three-dimensional models of plasma confinement systems, both the memory capacity and the speed of a Class VI system are prerequisites. Although idealized one- and

two-dimensional models have achieved successes, they have severe constraints. Complete three-dimensional models will enable simulation of existing confinement devices and eventual prediction of performance of planned devices.

In the spring of 1976, a review of computer use and projections was initiated. One specific facet of the review is an analysis of the need for, and the potential benefits of, a Class VI system in the NMFEECC. Recommendations about a schedule for acquisition of such a computer will result from the review.

C. Recent Achievements

1. Fusion Plasma Theory

Recent theoretical advances have been made in understanding plasma properties; plasma production and heating; atomic, molecular and nuclear physics; exploratory concepts; and computer applications of fusion plasma theory. The more prominent achievements in these problem areas are summarized below.

Plasma Properties - Theory

- A model was developed to explain the recently discovered Alcator result that the confinement time is directly proportional to the plasma density (MIT).
- A theoretical treatment has been developed to explain the 2XIIB mirror confinement time scaling (LLL).

- An impurity transport theory predicted that self purging of fusion-produced alpha particles in tokamaks occurs under certain conditions (MIT).
- A method was developed and applied to determine the effects of magnetic field inhomogeneities (ripple) on the efficiency of neutral beam heating in tokamaks (ORNL).
- Two distinct mechanisms have been analyzed to describe the observed evolution of internal disruptions in tokamaks (U. of Texas, GA).
- A generalized energy principle has been developed and applied to determine the stability of non-equilibrium plasma configurations, e.g., relativistic ion and electron rings (IAS, Cornell).
- A new analytic approach to nonlinear plasma problems has been formulated (IAS, U. of Rochester).
- A theoretical analysis of tokamak has established the diffusive nature of electron loss and, thus, an independent conformation of the scaling of confinement time with machine size (ORNL).
- Initial theory has been devised to describe flux conserving tokamaks (ORNL).
- The influence of the lower-hybrid-drift instability on post-implosion anomalous transport has been calculated for theta-pinch plasmas (U. of Maryland).

- A theoretical analysis of the nonlinear evolution of runaway electrons in tokamaks predicts a significant enhancement of cyclotron harmonic emission (U. of Maryland).
- Superlayer simulation code has shown existence of field reversed steady states apparently stable to Alfvén ion cyclotron mode (LLL).
- Scaling laws for the breakdown of the magnetic moment invariant (LLL).
- F-P based reactor studies (LLL).
- Atomic theory of negative ion sources (LLL).
- Increased theoretical understanding of the role of force free currents and noncircular cross sections on the MHD stability of high beta tokamaks (LASL).
- MHD computations of mass endloss from straight theta pinches which reproduce experimentally observed mass decay rates (LASL).
- Equilibrium and time dependent calculations of toroidal force balance in the Scyllac which definitely establish and give numerical values for the influence of diffuse plasma profiles (LASL, NRL).

Plasma Production and Heating - Theory

- Nonlinear absorption of RF near lower hybrid resonance at high pump strengths seems to lead to the excitations of only a few modes (PPPL).
- Calculations of threshold and growth rates for parametric instabilities caused by spatially localized pump waves show agreement with the ATC data (PPPL).
- Nonlinear heating mechanisms at high RF power levels have been shown to lead to effective energy transfer to the ions when the electric field of the wave is sufficient to trap the ion on a part of its cyclotron orbit (MIT).
- Preliminary fast ion deposition profiles for perpendicular neutral beam injection have been obtained (ORNL).
- Computations have been completed showing the feasibility of plasma heating by absorption of RF energy in the Alfvén continuum (NYU).
- Hybrid fluid particle computations of implosion heating which reproduce experimentally observed plasma profiles and dynamics in detail (LASL, SAI).

Atomic, Molecular and Nuclear Physics - Theory

This small theory program has only recently been organized and is not yet of sufficient size to address much of the required data. Nevertheless, very significant progress has been made.

- The role of dielectronic recombination has become much clearer as a result of detailed energy balance calculations for iron. The presence of dielectronic recombination tends to lower the ionized state obtained. If He-like ions (partially ionized atoms with only two electrons remaining) are thereby not obtained, the radiation loss is large. This is due primarily to collisional excitation and is sensitive to the dielectronic rate. If the temperature is sufficiently high to produce He-like ions regardless of dielectronic recombination, then the radiation losses are smaller and the rate need not be known accurately. Details vary for elements other than iron but a general statement is that dielectronic rates should be calculated accurately for elements heavier than iron and can be determined more approximately for lighter elements. Calculation of dielectronic recombination rates is much more complex for heavy elements. The most important process countering dielectronic recombination is collisional ionization. Reliable collisional ionization data are virtually unavailable.
- Energy levels and oscillator strengths (radiative transition rates) have been calculated for the principal series of Li-like (three electron) and Be-like (four electron) ions for essentially all

elements of interest in MFE (lithium through tungsten). Significant relativistic corrections are necessary for the heavy elements. Two separate calculations at NBS and Johns Hopkins are in substantial agreement and suggest that these transition rates are now adequately known for MFE purposes.

Exploratory Concepts - Theory

- Scaling laws for EBT based on neoclassical transport have been developed. These laws emphasize the importance of the ambipolar potential and aspect ratio for scaling to a reactor (ORNL, SAI).
- A description of MHD equilibria in Surmac has been developed (UCLA).
- A description of MHD equilibria in Tormac has been developed (PPPL).

Computer Applications - Theory

- Resistive equilibrium and stability models have now largely replaced ideal MHD codes.
- Diffuse profile calculations are now being performed to describe plasma transport; these give much more realistic estimates of temperature and density profiles than those previously given by sharp boundary models.
- Recently obtained results from the atomic physics research effort, including charge exchange cross sections, collisional excitation cross sections, dielectronic recombination rates, have been incorporated into models of impurity production and transport (PPPL, ORNL).

- Computer studies of neutral beam penetration into tokamak plasmas of circular and noncircular cross sections have been performed, and the results compared in detail with experiments on ORMAK. Models have been developed to study enhanced neutral beam penetration through ripples in the magnetic field (ORNL).
- Computer-aided analysis (MACSYMA) has made it possible to model the equations that govern lower hybrid resonance heating in confinement devices with various geometries (MIT).
- A code was developed to calculate synchrotron radiation from tokamaks and is being used to calculate radiation losses from TFR and Alcator (SAI).
- Computations have been completed showing the important influence of two-stage ionization and neutral-particle transport on theta pinch implosion profiles (U. of Maryland).
- Developed a 3-D equilibria code for minimum B mirrors (LLL).
- Developed a bounce average Fokker Planck code for parabolic fields (LLL).
- The quasilinear model of the Drift Cyclotron Loss Cone mode has been incorporated into the 2-D Fokker Planck Code (LLL).

2. Experimental Plasma Research

Major advances have been made recently in understanding experimental results concerning plasma properties; plasma production and heating; measurements and instrumentation; atomic, molecular and nuclear physics; and exploratory concepts. The more prominent achievements in these problem areas are summarized below.

Plasma Properties - Experimental

- Transport and Scaling Laws - Experimental measurements of plasma transport across the magnetic field in a toroidal octupole have verified the existence of Okuda-Dawson diffusion produced by convective cells. These experiments verify the predicted confinement time dependence on plasma density in the Okuda-Dawson regime ($\omega_{pe} \sim \omega_{ce}$). Diffusion in a purely poloidal magnetic field is dominated by vortex modes of an enhanced spectrum $D_{\perp} \sim 1/n$ independent of $|B|$ in the absolute minimum B region. With collisionless ions a new diffusion mechanism is observed due to low frequency fluctuations (Wisconsin).

The fabrication of a small tokamak device, Microtor, has been completed and preliminary testing initiated. This device will be used in conjunction with a larger device, Macrotor, for detailed measurements of energy and particle transport in tokamak devices (UCLA).

- Divertor Simulation - The design of a QED-1 device (quiet, energetic, dense plasma) was completed and assembly has been initiated. This device will be for divertor simulation experiments. One of the

solutions to the impurity problem expected in a fusion reactor is the use of divertors for impurity control (PPPL).

Electrostatic divertor action has been observed in the octupole (Wisconsin).

- High Beta Toroidal Configurations - Assembly of a rectangular cross section toroidal device (Torus I) has been completed and initial testing has begun. This device will test equilibrium and stability of various high beta, toroidal plasma configurations (Columbia).
- End Loss in Linear Systems - A complete analytic solution has been obtained for the static electron temperature distributions along a theta pinch in which heat flow out the ends of the pinch is balanced by electron-ion energy exchange. The solution is available for arbitrary spatial distributions of plasma density and ion temperature, and predicts electron temperature when ion temperature, plasma density and length of the system are specified. The experiment to evaluate these computations is nearing completion (LASL).

Plasma Production and Heating - Experimental

- RF Heating - ICRH (1 MW 2.6 MHz oscillator pump) studies in a small octupole has raised T_i from 1 eV to 350 eV with no deleterious effects except for a large reflux of neutrals from the wall. The observed heating agrees with stochastic heating theory with no parametric instabilities or enhanced diffusion (Wisconsin).

- Ion and Plasma Sources - A new type of H^- source was experimentally demonstrated. An H^- ion beam of 10 amps for a duration of 10 μ sec was observed when using a NaH target and a CO_2 laser beam in the 1-6 joule energy range with a pulse of 200 ns. The development effort for this source is now being pursued (by D&T) at TRW (UCLA).

A 6 kJ plasma accelerator (deflagration plasma gun) provides a plasma beam 3 mm in diameter and a directed velocity of $10^7 - 10^8$ cm/sec with a density of 10^{18} cm^{-3} for a time duration of 8 micro-seconds (Santa Clara).

- Implosion Heating - Implosion heating in a high voltage large bore linear theta pinch has demonstrated ion heating to temperatures about 10 keV with efficiencies for conversion of electrical energy transmitted into the theta pinch coil to plasma energy of about 20% (Maryland).

The preconization conditions and the implosion dynamics have been carefully studied in the IHX. The existence of a large fraction of particles moving ahead of the implosion sheath has been clearly demonstrated. Remarkable agreement with computer simulations is obtained (LASL).

Experimental verification that the immediate post-implosion resistivity in collisionless theta pinch plasmas can be 100 times classical (Maryland).

- Turbulent Heating - Experiments on TTT indicate that "fast" turbulent heating based on the Buneman instability does not seem to work in large plasmas (Texas).

Measurements and Instrumentation - Experimental

- Methyl fluoride laser sources (CH_3F) of 0.496 micron radiation (far infrared) have been developed using a high power CO_2 laser to pump an oscillator section and amplifier section. Over 200 k watts of CH_3F power has been generated. This is more than two orders of magnitude greater than previous CH_3F sources. Prospects are good for obtaining a further increase in power and narrowing the wavelength spread of radiation to the required limits (MIT, UCLA).
- Schottky barrier diodes for CH_3F detector systems of 10^{-16} watts/Hz noise equivalent power (NEP) are now routinely produced. A greatly improved NEP of 10^{-18} watts/Hz appears feasible by assembling diodes in microwave packages to increase coupling to the scattered radiation (MIT).
- An electrostatic multichannel neutral atom spectrometer to determine the ion energy distribution in Alcator has been built (MIT).
- An ion beam probe system has been operated successfully at LITE. This technique was developed under M&I support to measure plasma potential. Its use in LITE and projected use in EBT and TFTR is a direct result of continuing development of the procedure by the M&I program (RPI).

- A CO_2 laser forward scattering system has been demonstrated for measuring low frequency drift-type oscillations in plasmas. An optical homodyne detection technique is utilized and spurious scattering at angles of 2 to 10 milliradians is kept more than 8 to 10 orders below the power of the main beam (San Diego).
- A CO_2 laser has been used to heat a linear theta pinch and to study backscattered light. A new diagnostic development, time differential double pulse holographic interferometry, allow fractional fringe changes to be measured even when the total fringe count is too large to be resolved in end-on viewing (LASL).

Atomic, Molecular and Nuclear Physics - Experimental

- X-ray measurements in laser produced plasmas at NRL are now providing spectroscopic data of impurity elements. He-like (2 electron) ions up to chromium, Ne-like (10 electron) ions up to zirconium and Ni-like (28 electron) ions up to gold have been observed. Energy levels and spectral line identification for these ions have been obtained. Relativistic effects (for heavy elements) and screening effects (for light elements) are evident (NRL).
- Electron capture cross sections for C^{n+} , N^{n+} and O^{n+} in H_2 have been measured at ORNL for $n = 3, 4$ and 5. Also single and double charge transfer measurements of C^{4+} in helium have been obtained. The double charge transfer rates are surprisingly large. The energies of these measurements are appropriate

to a 0.5 to 10 keV plasma. This is some of the first data that has been generated by the AM&N program and represents a significant start towards meeting the needs for information on impurity ions (ORNL).

- Absolute cross sections for ionization of thalium ions by electron impact have been measured as a function of electron energy from below threshold to approximately 2 keV. These cross sections are required for the interpretation of thalium ion beam probe measurements of plasma temperature and density. Moreover the measurements have indicated the validity of simple calculation techniques for alkali-like systems and so allow the use of the calculations for other ion probes as well (Georgia Tech.).
- To supplement the impurity ion measurements at NRL, Maryland, Culham and Garching, a theta pinch facility has been placed in operation at NBS for use as a spectroscopic source for impurity ion measurements. Special digital timing circuits to control firing of the discharge banks and an automatic vacuum vessel filling system allow discharges to be highly reproducible. Elaborate two dimensional Thomson scattering equipment is operational and provides detailed measurement of the plasma distribution. Vacuum spectroscopic measurements in the $50\text{\AA}^{\circ}$ to $300\text{\AA}^{\circ}$ will provide cross section measurements of impurity ions (NBS).

- A compilation of cross sections for fusion research has been assembled with over 800 pages and 2500 data sheets. The compilation will be distributed in the summer of 1976 and is expected to become a standard reference for the CTR community. A bimonthly newsletter has continued to be distributed describing published and preliminary impurity data. More than 270 copies are distributed per issue (ORNL).

Fusion Plasma Research Facility - FPRF

- One of the primary recommendations of the Overview Panel in "The 1974 Review of the Research Program," ERDA-39, was to establish medium-scale confinement devices as research facilities to accommodate user groups from all sectors of the MFE program. In December 1974 an Ad Hoc Committee on Fusion Plasma Research Facilities was formed to further evaluate the need for and to determine characteristics of this kind of device. A report of the Committee, ERDA-106, concluded that one or more Fusion Plasma Research Facilities (FPRF) should be established consisting primarily of high duty-cycle, medium-scale, research-oriented confinement devices capable of producing plasmas with near thermonuclear parameters. A tokamak device was accorded the highest priority for the first FPRF. The Committee also recommended that the management of an FPRF involve representation of outside users as well as the institution that operates the facility.

The Ad Hoc Committee summarized the objectives for FPRF's in their overall order of importance as follows:

1. Provide atomic and molecular data required for analysis of plasma heating and cooling mechanisms, surface interactions and diagnostics.
2. Test, evaluate and standardize existing diagnostics and develop new diagnostic techniques.
3. Serve as a facility to test new ideas in order to improve plasma heating, equilibrium and stability.
4. Provide quantitative tests of theoretical plasma models, particularly large computer codes.
5. Train scientists directly on confinement devices.

Exploratory Concepts - Experimental

- Toroidal Systems - Tormac IV is demonstrating rf magneto-acoustic heating of collisional plasma at efficiencies of 25%. A much larger device, Tormac V, has recently been completed, and research on plasma heating and sheath structure has begun. Collisionless plasma of 300 eV ions are expected to be obtained by mid-CY 1976 (LBL).
- Linear Systems - New experimental devices, an 8 m multiple mirror system and relativistic electron beam-plasma interaction experiment, at University of California, Berkeley and University of California, Irvine, respectively, are being readied for initial operation this year. The first will be used to investigate end loss reduction in linear systems and the second for heating electrons/ions in linear geometry (Berkeley, Irvine).

- Linear Systems - A major experiment at MSNW is being readied to undertake a proof-of-principle experiment of the concept of employing long wavelength laser radiation to heat dense plasma confined in high magnetic fields. The 10 kJ CO₂ laser is scheduled for delivery in June 1976, and the 300 kG, 1 m long, magnet is undergoing initial testing (MSNW).
- Field Reversal - The reversal of initial confining fields by intense electron beams has been achieved for several years. The most recent work demonstrates ring lifetimes in excess of 2 msec (at 4 MeV electron energy) and field reversal for durations in excess of 100 μsec. Stabilization of these rings by toroidal magnetic fields has been established. Recent technological breakthroughs (60 nsec pulsed beams at 1 MeV and current levels of 200 kA, i.e., $> 1 \text{ kA/cm}^2$) in the generation of intense ion beams has opened up possibilities for various MFE applications. At present the most promising approach lies in establishing reversed field configurations either in minimum-B mirrors or as separate rings (Cornell).
- Liner Flux Compression - The liner flux compression experiment, LINUS, at the Naval Research Laboratory (NRL) has accomplished a most important objective. The Rayleigh-Taylor instability at peak compression and turn-around of the inner surface of the liquid liner has been suppressed by rotating the cylindrical liner at sufficient speed. Further a captive liner configuration has been conceived and model tested which allows cyclic reversible operation (NRL).

- Non-Magnetic Confinement - Multiple potential wells formed in the interior of an electrostatic confinement device have been predicted theoretically for a new 24 inch diameter device. Initial test results indicate that a ion rich inner potential region is being established at modest operating conditions. Investigations at higher confining potentials are underway (Illinois).

3. Computer Services and Technology

During FY 1976, the National MFE Computer Network became a reality. It was proposed as one of the three options for meeting MFE computer requirements in the July 1973 report, "The Application of Computers to Controlled Thermonuclear Research," (WASH-1296). Subsequently selected as the option with the most benefits, it was approved, a site for the Computer Center was selected, funds were provided, and equipment was procured within two years.

After delivery of equipment in the summer of 1975, there were acceptance tests, the installation of communications lines, and a major software development to provide for computer-to-computer communication through lines that spanned the country. The first successful significant transmissions over the dedicated Data Communications Network occurred in March 1976, but by that time the central computer was already saturated.

The existing Network includes the National MFE Computer Center (NMFECC) at Lawrence Livermore Laboratory (LLL), with a CDC 7600, and User Service Centers (USCs) with DEC PDP-10s at each of these sites: Princeton Plasma Physics Laboratory (PPPL), Oak Ridge National Laboratory (ORNL), Los Alamos Scientific Laboratory (LASL), General Atomic (GA), and the M-Division at LLL. The remote sites are linked to the Center by 50,000 bit-per-second dedicated communication lines. In addition to the dedicated lines, there is a capability at the NMFECC to service dial-up calls from low-speed terminals. This capability provides service to university and other sites as well as the interim service to the major laboratories.

The CDC 7600 was accepted in October 1975, and it is a testimonial to the computer requirements of the MFE community that this computer was saturated by January 1976, even though the Network was not operational until March 1976. In addition to the network software development effort, a number of computer science and engineering problems were solved. The NMFECC staff also prepared specifications and evaluated proposals for a mass storage device which will be installed at the Center at the end of the calendar year 1976. This unit will provide about one-half trillion bits of archival storage.

The PDP-10s in each USC had a minimal initial configuration that was augmented in FY 1976 through the installation of a second disk drive and additional core. At each site, staff learned the capabilities of the PDP-10 for small and medium-sized jobs, as well as its role as a terminal to the 7600. In several sites, plans proceeded for linking the PDP-10 to minicomputers used for data acquisition, with an attendant improvement in experimental data processing.

D. Program Structure, Budget Summary and Milestones

The Applied Plasma Physics Program activities are carried out within the framework of the three branches which span the major problem areas. Management of the program includes monitoring the progress made by contractors conducting investigations in the problem areas. One of the indicators of the progress is the completion of certain well defined phases of the projects under study. Completion of a phase is called a milestone. The branch budgets and milestones for the problem areas are given below.

1. Fusion Plasma Theory

Plasma Properties - Theory

<u>Research Activity</u>	<u>Projected Budget \$K</u>							
	<u>FY 1976</u>	<u>FY 1976T</u>	<u>FY 1977</u>	<u>FY 1978</u>	<u>FY 1979</u>	<u>FY 1980</u>	<u>FY 1981</u>	<u>FY 1982</u>
Tokamak	\$ 3,000	\$ 800	\$ 3,000	\$ 3,100	\$ 3,500	\$ 3,800	\$ 3,900	\$ 3,600
Advanced Concepts...	2,000	640	2,310	2,400	2,800	3,800	3,900	3,600
Supporting Physics..	0	0	0	130	700	600	500	1,200
Total Operating	\$ 5,000	\$ 1,440	\$ 5,310	\$ 5,630	\$ 7,000	\$ 8,200	\$ 8,300	\$ 8,400

Milestones

- | | |
|--|------------|
| 1. Quasilinear model of turbulent confinement in mirrors (LLL). | Achieved |
| 2. Determine transport and scaling arising from trapped particle instabilities
(Various sites). | Early 1976 |

3. Determine the detailed dependence of low frequency drift dissipative and trapped particle instabilities on system parameters and apply the results to fusion devices (PPPL, ORNL, Texas, NRL). Mid 1976
4. Determine the effect of impurities on plasma particle and heat transport, energy balance, and stability and apply the results to future fusion devices (various sites). Late 1976
5. Alfvén Ion Cyclotron Mode Stability boundaries (LLL). Late 1976
6. Quasilinear model of turbulent confinement in mirrors extended to model MX (larger radii) (LLL). Late 1976
7. Develop a theory of Guiding Center Stability for high beta 3-D minimum B mirror configurations (LLL). Early 1977
8. Q-enhancement to include but not exclusive; survey with bounced-averaged F.P., r.f. stoppering, high beta and reversed field configurations, time dependent mirror cycling (LLL). Mid 1977
9. Construction of a code to model neutral beam deposition into mirrors (LLL). Mid 1977
10. Theoretic models of negative ion formation implemented into computer codes (LLL). Late 1977
11. Quasilinear model of turbulent confinement in mirrors extended to model MX and incorporates radial transport due to turbulence (LLL). 1978
12. Develop nonlinear models to describe magnetic surface breakup and plasma transport associated with the disruptive instability, and other gross instabilities (site undetermined). 1979
13. Develop and apply new techniques for non-linear equations of plasma physics in complex realistic magnetic field configurations (various sites). 1977-1982

Plasma Production and Heating - Theory

Research Activity	Projected Budget \$K							
	FY 1976	FY 1976T	FY 1977	FY 1978	FY 1979	FY 1980	FY 1981	FY 1982
Tokamak	\$ 500	\$ 140	\$ 520	\$ 700	\$ 830	\$ 1,000	\$ 1,000	\$ 900
Advanced Concepts ...	0	0	0	300	390	480	500	600
Supporting Physics...	0	0	0	0	0	0	0	0
Total Operating	\$ 500	\$ 140	\$ 520	\$ 1,000	\$ 1,220	\$ 1,480	\$ 1,500	\$ 1,500

Milestones

- | | |
|---|----------------------|
| 1. Derive a generalized formulation of ponderomotive effects for nonlinear interactions in a magneto plasma (LBL). | Jan. 1976 (Achieved) |
| 2. Determine the nonlinear processes involved in lower hybrid plasma heating (Stevens). | Jan. 1976 (Achieved) |
| 3. Extend the development of two-dimensional time-dependent transport codes and apply to auxiliary heating for current profile control (GA). | Feb. 1976 (Achieved) |
| 4. Investigate diffusion and heating of particles by a single oblique wave in a magneto plasma as a heating method (LBL). | June 1976 (Achieved) |
| 5. Determine the characteristics of waves in periodically varying magnetic fields (SAI). | June 1976 (Achieved) |
| 6. Examine the growth rate of instabilities produced by lower hybrid pump waves to study plasma heating by the lower hybrid pump (Iowa). | June 1976 (Achieved) |
| 7. Extend present initial dynamics codes for screw pinches and belt pinches to high beta tokamaks and helical systems. They will also be extended to longer running times so as to obtain the approach to equilibrium (Columbia). | Aug. 1976 |
| 8. A complete initial study of nonlinear concepts of velocity space in stabilities associated with intense parallel or perpendicular heating injections (PPPL). | Dec. 1976 |
| 9. Assess the theoretical expectations for all heating in large tokamaks, considering nonlinear limits on lower hybrid heating, and for Fokker-Planck simulations of ion-cyclotron heating (PPPL). | Dec. 1976 |
| 10. Develop a theoretical description of RF heating, including lower hybrid, ICRH, and Alfvén and apply the results to confinement devices (PPPL), (ORNL). | Feb. 1977 |
| 11. Study the dynamics of L-H heating for tokamak applications (MIT). | Oct. 1977 |
| 12. Develop nonlinear theories to determine saturation levels and anomalous transport coefficients in high beta confinement systems (Maryland). | Oct. 1977 |
| 13. Complete application of hybrid kinetic model to determine influence of finite electron pressure and electron kinetic effects on theta pinch stability behavior (Maryland). | Oct. 1977 |
| 14. Complete investigation of classical neutral beam energy deposition in a tokamak (ORNL), (PPPL). | Nov. 1977 |

Atomic, Molecular and Nuclear Physics - Theory

Research Activity	Projected Budget \$K							
	FY 1976	FY 1976T	FY 1977	FY 1978	FY 1979	FY 1980	FY 1981	FY 1982
Tokamak	\$ 330	\$ 100	\$ 470	\$ 820	\$ 990	\$ 1,100	\$ 1,000	\$ 850
Advanced Concepts...	0	0	0	0	0	0	0	0
Supporting Physics...	0	0	0	0	0	0	0	0
Total Operating	\$ 300	\$ 100	\$ 270	\$ 820	\$ 990	\$ 1,100	\$ 1,000	\$ 850

Milestones

1. Complete examination of bremsstrahlung, ionization and radiative excitation processes which occur between an electron and a partially stripped ion and apply the results to operating confinement systems (Sandia). Mid 1976
2. Calculate synchrotron radiation from tokamak plasmas (SAI). Mid 1977
3. Calculate nuclear cross sections in close support of experimental effort (site undetermined). Mid 1977
4. Complete study of recombination processes under same conditions as above (IASL, NBS, Universities). Early 1978
5. Perform theoretical calculations of surface physics and apply these to existing and future confinement devices (site undetermined). Early 1979

Exploratory Concepts - Theory

Research Activity	Projected Budget \$K							
	FY 1976	FY 1976T	FY 1977	FY 1978	FY 1979	FY 1980	FY 1981	FY 1982
Tokamak	\$ 0	\$ 0	\$ 0	\$ 0	\$ 0	\$ 0	\$ 0	\$ 0
Advanced Concepts...	0	0	0	1,250	1,290	1,420	1,350	1,250
Supporting Physics...	0	0	0	0	0	0	0	0
Total Operating	\$ 0	\$ 0	\$ 0	\$ 1,250	\$ 1,290	\$ 1,420	\$ 1,350	\$ 1,250

Milestones

- | | |
|--|----------------------|
| 1. Develop a numerical code to solve 3-D equilibrium for EBT (high-beta, anisotropy realistic radial profiles (ORNL)). | Jan. 1976 (Achieved) |
| 2. Provide a theoretical capability in support of TORMAC at LBL (DMFE) | Oct. 1976 |
| 3. Develop a hybrid code for study of low frequency modes in ion rings (Cornell). | Dec. 1976 |
| 4. Apply the new description of plasmas developed at Boston College to TORMAC (PPPL). | June 1977 |

Computer Applications - Theory

Research Activity	Projected Budget \$K							
	FY 1976	FY 1976T	FY 1977	FY 1978	FY 1979	FY 1980	FY 1981	FY 1982
Tokamak.....	\$ 3,600	\$ 1,000	\$ 4,000	\$ 5,000	\$ 5,700	\$ 7,000	\$ 7,100	\$ 7,100
Advanced Concepts ...	2,590	800	3,000	3,600	4,400	5,300	5,400	5,400
Supporting Physics...	280	120	300	400	400	500	350	500
Total Operating	\$ 6,470	\$ 1,920	\$ 7,300	\$ 9,000	\$10,500	\$12,800	\$12,850	\$13,000

Milestones

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|---|----------------------|
| 1. Develop a numerical technique which will evolve into a production code for solving 2D initial value problems for ideal MHD and realistic equilibria (various sites). | July 1975 (Achieved) |
| 2. Complete preliminary calculations of the mode structure of lower hybrid heating for application to ATC (PPPL). | July 1975 (Achieved) |
| 3. Complete initial phase of calculations of equilibrium and stability of PDX using codes developed in FY 1973/74 (PPPL). | July 1975 (Achieved) |
| 4. Complete preliminary calculation of the opacity to cyclotron (synchrotron) radiation of an equilibrium plasma as a function of frequency, direction, and polarization (SAI). | Fall 1975 (Achieved) |

5. Develop and apply 1-D hybrid code to tokamak geometry for the study of skin phase of discharge (SAI, PPPL, ORNL)	Fall 1975 (Achieved)
6. Complete preliminary calculations for mirror systems using Fokker-Planck codes with neutral beam injection, charge exchange, and ionization effects included (LLL).	Fall 1975 (Achieved)
7. Computer simulation of high β mirrors and field-reversed configurations (LLL).	Late 1975 (Achieved)
8. Develop a 2-D transport code for non-circular cross sections that will be applied to the Doublet machines prior to the formation of magnetic x-points (SAI).	July 1977 (Achieved)
9. Modify bounce averaged Fokker-Planck code to include:	
(a) coupling to quasilinear turbulence model (LLL)	Mid 1976
(b) general field shapes (LLL)	Late 1976
(c) include effects of magnetic moment invariant breakdown (LLL)	Late 1976
(d) development of multispecies version (LLL)	Mid 1977
(e) coupling to enhanced scattering due to convective loss modes (LLL)	Mid 1977
10. Complete investigation of classical neutral beam energy deposition in a tokamak (PPPL, ORNL, GA, MIT).	Early 1977
11. Develop a theoretical description of RF heating, including lower hybrid, ICRH, and Alfvén and apply the results to confinement devices (PPPL).	Mid 1977
12. Develop a hybrid code to describe implosion heating and profile evaluation in THOR-toroidal theta pinch (Maryland).	June 1977
13. Couple 3-D high β equilibrium code to F.P. and radial buildup codes (LLL).	Mid 1977
14. Conduct MHD stability studies for geometry and parameters appropriate to TERP-high beta tokamak (Maryland).	Oct. 1977
15. Develop realistic time-dependent macroscopic fluid models to describe plasmas on the fast Alfvén time scale and on the slower magneto-acoustic time scale (site undetermined).	Late 1977
16. Update the physics of high beta mirror and field-reversal codes to include electron dynamics and effects of electromagnetic instabilities (LLL).	Late 1977
17. Develop code to model gas feed experiments in mirrors (LLL).	1978
18. Develop and apply realistic particle simulation codes (site undetermined).	1978
19. Complete analysis of the production and effects of electron runaways (ORNL, MIT, NRL).	1978
20. Develop and apply realistic 3-D codes to describe MHD equilibrium and evaluate stability criteria (IASL, NYU, ORNL, PPPL).	1978

21. Describe the equilibrium, stability, and transport of a two-component reactor in tokamak geometries (PPPL). 1978
22. Model the plasma physics in the vicinity of the scrape off region of a divertor (PPPL). 1978
23. Develop realistic distribution function codes (ORNL). 1979
24. Develop codes to model burning plasma systems, including reactors and apply these to reactor designs (site undetermined). 1979

2. Experimental Plasma Research

Plasma Properties - Experimental

Research Activity	Projected Budget \$K							
	FY 1976	FY 1976T	FY 1977	FY 1978	FY 1979	FY 1980	FY 1981	FY 1982
Transport and Scaling Laws.....	\$ 830 (340)	\$ 405 (300)	\$ 1,345 (150)	\$ 1,300 (180)	\$ 1,570 (200)	\$ 1,630 (230)	\$ 1,535 (150)	\$ 1,450 (200)
Divertor Simulation...	140 (20)	115 (20)	225 (10)	185 ()	230 (100)	260 (50)	200 (50)	155 (50)
High Beta Toroidal ...	320 (205)	150 ()	330 (250)	520 (220)	625 (150)	610 (100)	525 (100)	465 (50)
End Loss	300 (60)	55 (5)	225 (15)	295 ()	275 (50)	300 (70)	240 (50)	230 (50)
Total Operating	\$ 1,590	\$ 725	\$ 2,125	\$ 2,300	\$ 2,700	\$ 2,800	\$ 2,500	\$ 2,300
Equipment	(625)	(325)	(425)	(400)	(500)	(450)	(350)	(350)

Milestones (Transport and Scaling Laws)

1. Move levitated octupole from the remote site to the campus (U. of Wisc.) November 1974 (Achieved)
2. Complete experimental investigations of the effects of intense EM heating fields on collision rates (LASL). July 1975 (Achieved)

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|---|--------------------------|
| 3. Complete fabrication and begin operation of Microtor, a small tokamak device for energy and particle transport studies (UCLA). | November 1975 (Achieved) |
| 4. Complete measurements and identification of lower hybrid resonance effects in a linear device (UCLA). | Dec. 1975 (Achieved) |
| 5. Complete measurements and analysis to determine the mechanisms which generate runaway electrons in a typical Ormak discharge (ORNL). | June 1976 (Achieved) |
| 6. Complete the study of ion-cyclotron instabilities driven by ion beam injection (PPPL). | June 1976 (Achieved) |
| 7. Complete Major Device Fabrication Review (MDFR) for the Microtor/Macrotror project. Project approved for fabrication, operation and experimental investigation with Macrotror B _T up to 10 kG (UCLA). | June 1976 (Achieved) |
| 8. Complete preliminary impurity control investigations as to their effects on tokamak scaling laws (UCLA). | Jan. 1977 |
| 9. Complete fabrication and begin operation of Versator II (MIT). | Jan. 1977 |
| 10. Achieve an understanding of studies of B independent of 1/n diffusion (U. of Wisc.). | May 1977 |
| 11. Achieve an understanding of diffusion scaling for the trapped ion regime (U. of Wisc.). | May 1977 |
| 12. Complete the assessment of the role of runaway electrons on plasma stability, equilibrium and impurity evolution (ORNL). | June 1977 |
| 13. Obtain preliminary results of the transport effects due to trapped ion instabilities in a levitated octupole (U. of Wisc.) | June 1977 |
| 14. Major Device Fabrication Review (MDFR) to upgrade Macrotror to B _T of 30 kG (UCLA). | Jan. 1978 |
| 15. Complete the study of skin effect and channel formation in the limits of strong and weak ohmic heating (UCLA). | |

Milestones (Divertor Simulation)

- | | |
|--|----------------------|
| 1. Complete assembly of the QED-1 device for divertor simulation studies (PPPL). | June 1976 (Achieved) |
| 2. Complete detailed measurements of scrape-off zone plasma with existing source using the single ring DC Machine (Wisconsin). | Dec. 1976 |
| 3. Extend the electrostatic divertor geometry and plasma parameters in the octupole (Wisconsin). | Dec. 1976 |
| 4. Complete preliminary experimental test of Tenney gaseous collector model for a divertor (PPPL). | June 1977 |

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|--|------------|
| 5. Complete preliminary electrostatic divertor action studies caused by $E \times B$ drifts in the levitated octupole (U. of Wisconsin). | Aug. 1977 |
| 6. Complete measurements and analysis of scrape-off zone plasma with higher density source using the single ring DC machine (Wisconsin). | Sept. 1977 |
| 7. Complete evaluation of shock formation at the plasma-gas interface of Tenney gaseous collector (PPPL). | Jan. 1978 |
| 8. Complete the evaluation of emission of impurities by the divertor into the main plasma (PPPL). | June 1978 |

Milestones (High Beta Toroidal)

- | | |
|---|-----------------------|
| 1. Begin operating Torus I in belt pinch mode (Columbia). | Nov. 1975 (Achieved) |
| 2. Begin operating Torus I in high beta tokamak mode (Columbia). | Jan. 1976 (Achieved) |
| 3. Complete Major Device Fabrication Review (MDFR) for Torus II. Torus II approved for fabrication, operation and high beta experimental investigations (Columbia). | April 1976 (Achieved) |
| 4. Complete preliminary survey of Torus I operation as a belt pinch (Columbia). | June 1976 (Achieved) |
| 5. Complete preliminary survey of Torus I operation in a high beta tokamak mode (Columbia). | Sept. 1976 |
| 6. Complete B, n, T and v measurements for the study of equilibrium, transport and stability in the collisional (P-S) non-circular high beta tokamak regime (Maryland). | Dec. 1976 |
| 7. Major Device Fabrication Review (MDFR) to evaluate upgrading TERP to investigate high beta equilibrium, transport and stability in the neo-classical regime (Maryland) | Jan. 1977 |
| 8. Complete compression, ohmic heating, equilibrium and stability studies in Torus I (Columbia). | Oct. 1977 |
| 9. Complete assembly and begin operation of Torus II (Columbia). | Jan. 1978 |
| 10. Complete preliminary survey of Torus II operation (Columbia). | Summer 1978 |

Milestones (End Loss)

- | | |
|--|------------|
| 1. Complete the measurements and analysis of transient flow from a 25 cm linear theta pinch (Penn State) | March 1977 |
| 2. Complete assembly and preliminary testing of a 50 cm linear theta pinch with crowbar and mirror circuitry (Penn State) | March 1977 |
| 3. Complete the investigations of the effects of electrostatic trapping potentials on heat flow in a linear magnetically confined plasma (IASL). | June 1977 |
| 4. Complete preliminary measurements of end loss processes with mirrors in a linear theta pinch (Penn State). | Oct. 1977 |
| 5. Complete measurements of end loss processes with mirrors in a linear theta pinch (Penn State). | Oct. 1978 |

Plasma Production and Heating - Experimental

Research Activity	Projected Budget \$K							
	FY 1976	FY 1976T	FY 1977	FY 1978	FY 1979	FY 1980	FY 1981	FY 1982
RF Heating	\$ 690 (70)	\$ 300 (30)	\$ 1,605 (100)	\$ 1,890 (100)	\$ 2,010 (200)	\$ 2,200 (200)	\$ 2,025 (100)	\$ 1,980 (150)
Ion and Plasma Sources.	305 (70)	70 (20)	325 (20)	510 (100)	590 (200)	600 (100)	575 (100)	520 (50)
Implosion Heating.....	815 (220)	165 (75)	450 (30)	0	0	0	0	0
Turbulent Heating	850 (115)	200	0	0	0	0	0	0
Total Operating	\$ 2,660	\$ 735	\$ 2,380	\$ 2,400	\$ 2,600	\$ 2,800	\$ 2,600	\$ 2,500
Equipment.....	(475)	(125)	(150)	(200)	(400)	(300)	(200)	(200)

Milestones (RF Heating)

1. Complete quantitative measurements of OH, ICRH and ECRH on the supported octupole for q values near the tokamak regime (Wisconsin). June 1975 (Achieved)
2. Complete assembly and begin initial operation of a research tokamak for plasma heating studies (Cal. Tech.). Feb. 1976 (Achieved)
3. Complete the efficiency and spatial localization investigations of LHRH in a linear device and initiate ICRH studies (PPPL). June 1976 (Achieved)
4. Complete the study of ICRH wave penetration and absorption as a function of toroidal field strength and plasma density in a supported octupole at a power level of 1 MW (Wisconsin). June 1976 (Achieved)
5. Modify ICRH system to raise T_i to 800 eV. Present system - T_i increases from 1 eV to 350 eV with 1 MW (Wisconsin). Nov. 1976
6. Determine the feasibility of ECR breakdown in a simulated tokamak plasma and the effectiveness of ECRH for discharge cleaning (Wisconsin). Nov. 1976
7. Test penetration of LH waves in octupole plasmas at 1 kW level. If successful extend to 10 kW level (Wisconsin). Nov. 1976
8. Complete preliminary measurements and analysis of ICR wave mode structure, propagation characteristics and energy deposition mechanisms (Cal. Tech.) May 1977

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|---|-----------|
| 9. Complete preliminary survey of spontaneous radiation in the microwave range to determine whether significant radiation near the ion plasma frequency is present, as observed in Alcator (Cal. Tech.) | May 1977 |
| 10. Complete the efficiency, wave absorption and spatial localization investigations of ICRH in a linear device (PPPL). | June 1977 |
| 11. Complete coupler design, wave absorption and efficiency studies for ICRH in a research tokamak (Cal. Tech.) | Jan. 1978 |
| 12. Complete preliminary coupler design, wave absorption and efficiency studies for LH heating in a research tokamak (Cal. Tech.). | June 1978 |

Milestones (Ion and Plasma Sources)

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|--|-------------------------|
| 1. Complete the production of a beam of negative (H ⁻) ions using a NaH target irradiated with a CO ₂ laser beam (UCLA). | Oct. 1974 (Achieved) |
| 2. Initial test results for a plasma accelerator (deflagration plasma gun) designed for a pulse duration of 50 to 100 μ sec (Santa Clara). | May 1976 (Achieved) |
| 3. Complete the evaluation of the best cathode configuration for a neutral beam source (MIT). | June 1976 (Achieved) |
| 4. Complete measurements and evaluation of the electrical and gas flow efficiency, beam divergence and ionic composition of a typical LBL neutral beam source (LBL). | Sept. 1976
Jan. 1977 |
| 5. Complete the design of an improved positive ion source (LBL, MIT). | Jan. 1977 |
| 6. Complete testing and analysis of three plasma guns (6, 12 and 50 kJ) to determine the required scaling laws (Santa Clara). | Jan. 1977 |
| 7. Complete experimental investigations necessary to verify that a 1 to 5 amps negative ion source can be developed using production at a solid surface (LBL). | June 1978 |

Milestones (Implosion Heating)

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|--|----------------------|
| 1. Complete assembly and begin operation of the linear Implosion Heating Experiment - IHX (IASL). | Feb. 1975 (Achieved) |
| 2. Complete the evaluation of neutral background effects on magnetic piston and current sheath development in a linear theta pinch (Texas). | Feb. 1976 (Achieved) |
| 3. Complete assembly and begin operation of a toroidal shock heated theta pinch - THOR (Maryland). | Aug. 1976 |
| 4. Complete measurements and analysis of the ion heating dependence on plasma density and piston amplitude in a linear theta pinch - IHX (IASL). | Sept. 1976 |

5. Preliminary plasma parameter measurements for implosion heating in a toroidal configuration (Maryland). Dec. 1976
6. Complete implosion heating investigations and analysis for the toroidal configuration - THOR (Maryland). Oct. 1977

Milestones (Turbulent Heating)

1. Complete ion-acoustic turbulence studies (Maryland). Dec. 1975 (Achieved).
2. Transfer TTT experiment from Confinement Systems to Applied Plasma Physics (Texas). Dec. 1975 (Achieved)
3. Complete turbulence/REB heating studies in a mirror geometry (Cornell) Jan. 1976 (Achieved)
4. Complete the evaluation of the experimental results as compared to the theoretical predictions for turbulent heating in TTT (Texas). Oct. 1976

Measurements and Instrumentation - Experimental

<u>Research Activity</u>	<u>Projected Budget \$K</u>							
	<u>FY 1976</u>	<u>FY 1976T</u>	<u>FY 1977</u>	<u>FY 1978</u>	<u>FY 1979</u>	<u>FY 1980</u>	<u>FY 1981</u>	<u>FY 1982</u>
New Diagnostic Techniques	\$ 820 (305)	\$ 310 (140)	\$ 1,740 (305)	\$ 2,385 (300)	\$ 2,470 (400)	\$ 2,570 (300)	\$ 2,300 (200)	\$ 2,100 (200)
Advanced Data Acquisition	90 (70)	30 (10)	200 (45)	300 (50)	320 (50)	345 (75)	400 (100)	400 (100)
Measurement Standards.	150	40	160	150 (50)	160 (50)	185 (75)	200 (50)	200 (50)
Total Operating	\$ 1,060	\$ 340	\$ 2,100	\$ 2,735	\$ 2,950	\$ 3,100	\$ 2,900	\$ 2,700
Equipment.....	(375)	(150)	(350)	(400)	(500)	(450)	(350)	(350)

Milestones (New Diagnostic Techniques)

- | | |
|---|-----------------------|
| 1. Complete preliminary testing of a CH ₃ F laser providing over 200 kW of 0.496 micron radiation (MIT). | March 1976 (Achieved) |
| 2. Complete the assembly of an electrostatic multichannel neutral atom spectrometer for Alcator (MIT). | April 1976 (Achieved) |
| 3. Complete preliminary testing of a CO ₂ forward scattering and an optical homodyne detection system to measure low frequency drift-type oscillations in plasma (UCSD). | May 1976 (Achieved) |
| 4. Operate 1 MV CH ₃ F laser pumped by 150 J CO ₂ laser (ORNL) | Jan. 1977 |
| 5. Operate CH ₃ F laser interferometer on ORMAK (ORNL). | Jan. 1977 |
| 6. Measure synchrotron emission on PLT (Maryland). | April 1977 |
| 7. Develop 200 kW far IR CH ₃ F laser system with 10 ⁻¹⁸ watts/Hz Schottky detectors (MIT). | |
| 8. Compare ion beam temperature measurements with Thomson scattering measurements on a Versator type of Tokamak (RPI). | July 1977 |
| 9. Develop small extreme UV and soft x-ray spectrographic equipment and measure impurity concentrations on Tokamaks (Johns Hopkins, NRL). | Aug. 1977 |
| 10. Develop and test CO ₂ forward scattering techniques for density fluctuation measurements (UCSD, MIT). | Oct. 1977 |
| 11. Develop high resolution x-ray spectrometer for Ti measurement by Doppler broadening (Harvard). | Dec. 1977 |
| 12. Install CH ₃ F laser system on plasma device (MIT, ORNL). | Jan. 1978 |
| 13. Develop B-field measurement techniques from optical emissions from probe beams (MIT, undesignated). | April 1978 |
| 14. Develop current density measurement techniques (RPI, Others). | June 1978 |

Milestones (Advanced Data Acquisition)

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|---|-----------|
| 1. Develop space-resolved Thomson scattering instrumentation for theta pinch plasmas (IASL). | Oct. 1977 |
| 2. Develop instrumentation for storage retrieval, processing and display of signals in flexible formats including two dimensional displays of signals (IASL). | Oct. 1978 |

Milestones (Measurement Standards)

- | | |
|---|----------------------|
| 1. Complete the UV radiometric standards facility (SURF-II) and begin calibrating spectrometer equipment (NBS). | Jan. 1976 (Achieved) |
| 2. Complete neutron standards measurements for CTR using ^{235}U , ^{237}Np and ^6Li (NBS). | June 1976 (Achieved) |
| 3. Develop monoenergetic K x-ray beams at less than 1.5 keV beam energy and at higher intensities than currently available sources (NBS). | Jan. 1977 |
| 4. Develop simple low cost UV calibration sources (undesignated). | Jan. 1978 |
| 5. Provide standard sources and calibration facilities for CTR spectroscopy (NBS). | Jan. 1979 |

Atomic, Molecular and Nuclear Physics - Experimental

Research Activity	Projected Budget \$K							
	FY 1976	FY 1976T	FY 1977	FY 1978	FY 1979	FY 1980	FY 1981	FY 1982
Impurity Data	\$ 1,015 (125)	\$ 360 (20)	\$ 1,540 (50)	\$ 1,880 (100)	\$ 1,950 (200)	\$ 1,900 (100)	\$ 1,800 (50)	\$ 1,700 (25)
Surface Effects	75	10	170	370	600 (150)	825 (100)	900 (25)	900 (25)
Data Centers	150	60	210	220	260 (50)	275 (50)	300 (25)	250 (25)
Nuclear Data	50	15	80	230	290 (100)	500 (100)	600 (150)	650 (175)
Total Operating	\$ 1,290	\$ 445	\$ 2,000	\$ 2,700	\$ 3,100	\$ 3,500	\$ 3,600	\$ 3,500
Equipment	(125)	(20)	(50)	(100)	(500)	(350)	(250)	(250)

Milestones (Impurity Data)

- | | |
|---|----------------------|
| 1. Complete absolute cross section measurements for thallium by electron impact ionization for electron energies up to 2 keV (Ga. Tech.). | Jan. 1975 (Achieved) |
| 2. Complete absolute electron impact ionization cross section measurements for Cs^+ and Rb^+ . | Aug. 1975 (Achieved) |

3. Complete assembly and initial tests of a theta pinch facility (NBS).	Jan. 1976 (Achieved)
4. Complete electron capture cross sections for C^{n+} , N^{n+} and O^{n+} in H_2 for $n = 3, 4$ and 5 (ORNL).	June 1976 (Achieved)
5. Initiate rate coefficient measurements in theta pinch facility (NBS).	June 1976 (Achieved)
6. Complete electron-impact excitation and ionization cross section measurements for Li-like ions (Be II, C IV, O VI). (JILA).	Dec. 1976
7. Complete charge exchange cross section measurements of C^{n+} , O^{n+} and Fe^{n+} with H^0 energy range 20-150 keV (ORNL).	Dec. 1976
8. Measure and interpret Mo and Au x-ray wavelengths in laser and spark plasmas (NRL).	April 1977
9. Complete ionization cross section measurements for H^0 on C^{n+} , O^{n+} , N^{n+} and Fe^{n+} (ORNL).	Jan. 1978
10. Determine primary processes and reaction rates for formation of negative deuterium ion in gases and at surfaces (LBL, SRI).	Jan. 1978
11. Extend electron cross section measurements to heavy impurities (JILA, ORNL, NBS).	June 1978
12. Identify resonance lines for one-electron and rare-gas-like ions of heavy elements through Au XI and Au XII (NBS).	Sept. 1978
13. Complete development of negative ion source theoretical model (LBL).	Jan. 1979
14. Obtain stripping data for deuterium beams in relevant target gases (LBL)	March 1979
15. Extend charge exchange measurements to heavy elements (ORNL, LBL, NRL).	Jan. 1980
16. Provide tables of x-ray and UV lines of CTR interest to between 0.01 and 0.1 Å accuracy (NBS, NRL, Others).	March 1980
17. Provide data for EPR neutral beam development (LBL, SRI, Others)	March 1980

Milestones (Surface Effects)

1. Complete H^0 reflection measurements of energy and angular distributions (ORNL).	Oct. 1976
2. Measure charge state distribution and excited state percentages of backscattered H atoms when 5-30 keV H^+ , H^0 and H_2^+ are incident on C, Au, Nb, Ta and W targets (Ga. Tech.).	Feb. 1977
3. Obtain reflected neutral particle data as a function of energy (ORNL, Ga. Tech.).	Jan. 1979
4. Determine charged particle emission from surfaces by scattering of incident particles (Ga. Tech., ORNL).	June 1979

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|---|------------|
| 5. Complete measurements of D ⁰ desorption by photons, electrons and deuterium (ORNL, U. Va.). | Jan. 1980 |
| 6. Provide surface data for EPR design. | March 1980 |
| 7. Characterize plasma impurity contamination by deuterium and neutron sputtering (undesignated). | June 1980 |

Milestones (Atomic Data Center)

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|--|------------|
| 1. Compile, evaluate and distribute atomic data. | Continuing |
| 2. Initiate critical evaluation of atomic data. | Oct. 1977 |
| 3. Provide computer access to data by terminals. | June 1979 |

Milestones (Nuclear Data)

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|--|------------|
| 1. Complete D-T cross section measurement (NBS). | Oct. 1976 |
| 2. Initiate expanded program in nuclear dosimetry and breeding data (NBS, IASL). | March 1977 |
| 3. Initiate program on neutron detection for Ti diagnostics (undesignated). | Oct. 1979 |
| 4. Provide breeding, dosimetry and diagnostics data for EPR design. | March 1980 |

Fusion Plasma Research Facility - FPRF

<u>Research Activity</u>	<u>Projected Budget \$K</u>							
	<u>FY 1976</u>	<u>FY 1976T</u>	<u>FY 1977</u>	<u>FY 1978</u>	<u>FY 1979</u>	<u>FY 1980</u>	<u>FY 1981</u>	<u>FY 1982</u>
FPRF Operating	\$ 0	\$ 0	\$ 3,000	\$ 3,000	\$ 2,500	\$ 2,600	\$ 2,700	\$ 2,800
Equipment			(1,000)	(1,000)	(600)	(650)	(700)	(500)

Milestones

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|---|-----------------|
| 1. Report of the Ad Hoc Committee on Fusion Plasma Research Facilities completed, ERDA-106. | 1975 (Achieved) |
| 2. Major Device Fabrication Review (MDFR) for a proposed FPRF - tokamak type (Texas). | Aug. 1976 |
| 3. Complete final conceptual designs (Texas). | Feb. 1977 |
| 4. Complete assembly and test of first homopolar generator (Texas). | Feb. 1978 |
| 5. Complete tokamak facility assembly and test (Texas). | Feb. 1979 |

Exploratory Concepts - Experimental

<u>Research Activity</u>	<u>Projected Budget \$K</u>							
	<u>FY 1976</u>	<u>FY 1976T</u>	<u>FY 1977</u>	<u>FY 1978</u>	<u>FY 1979</u>	<u>FY 1980</u>	<u>FY 1981</u>	<u>FY 1982</u>
Toroidal Systems	\$ 150	\$ 60	\$ 400 (50)	\$ 1,100 (500)	\$ 1,050 (500)	\$ 1,600 (500)	\$ 1,000 (300)	\$ 1,100 (600)
Linear Systems	1,630 (665)	600 (80)	1,695 (100)	700 (100)	700 (200)	650 (400)	700 (500)	600 (200)
Field Reversal	275 (35)	25	850 (75)	965 (100)	1,000 (700)	1,200 (200)	2,600 (950)	3,100 (1,400)
Liner Flux Compression.	100	115	1,250 (200)	1,300 (100)	1,400 (500)	1,400 (700)	1,400 (400)	1,400 (650)
Non-Magnetic Confinement	45	55		200 (100)	300 (100)	350	0 0	0 0
Total Operating	\$ 2,200	\$ 855	\$ 4,195	\$ 4,265	\$ 4,450	\$ 5,200	\$ 5,700	\$ 6,200
Equipment	(700)	(80)	(425)	(900)	(2,000)	(1,800)	(2,150)	(2,850)

Milestones

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|--|----------------------|
| 1. Preliminary experimental results on plasma heating with a rotating relativistic E-beam (UC/Irvine). | June 1976 (Achieved) |
| 2. Produce plasma confinement in enlarged electro-static well (Illinois). | June 1976 (Achieved) |
| 3. Begin investigation of stabilization of presently known instabilities in E-layers in as Astron type facility (Cornell). | Aug. 1976 |
| 4. Experimental determination of plasma heating rates using weak shock heating in Tormac (Shaker) experiment (LBL). | Aug. 1976 |
| 5. Initiate staged heating experiment in CO ₂ laser heated solenoid (MSNW, Washington). | Aug. 1976 |

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|---|------------|
| 6. Production of high aspect ratio CO ₂ laser-heated, dense, magnetized plasma (MSNW). | Dec. 1976 |
| 7. Begin operation of improved multiple mirror confinement experiment (UC/Berkeley). | Dec. 1976 |
| 8. Determine Tormac sheath structure (LBL). | Dec. 1976 |
| 9. Begin start-up and refueling experiments in Tormac program (LBL). | March 1977 |
| 10. Begin captive liner flux compression experiments (NRL). | March 1977 |
| 11. Evaluate plasma formation experiments for liner compression experiments (NRL). | July 1977 |
| 12. Preliminary results for proof-of-concept for CO ₂ laser heated solenoid (MSNW). | July 1977 |
| 13. Initiate studies of plasma confinement in electron ring field reversed configuration (Cornell). | March 1978 |
| 14. Complete proof-of-concept experiment for CO ₂ laser heated solenoid (MSNW). | 1979 |

3. Computer Services and Technology

	Projected Budget \$K							
	<u>FY 1976</u>	<u>FY 1976T</u>	<u>FY 1977</u>	<u>FY 1978</u>	<u>FY 1979</u>	<u>FY 1980</u>	<u>FY 1981</u>	<u>FY 1982</u>
Operating Budget	\$ 3,200	\$ 1,100	\$ 5,000	\$ 9,000	\$ 8,700	\$10,000	\$10,000	\$10,000
Equipment Budget	2,100	300	5,600	2,000	3,900	15,000	2,100	10,200
Construction Budget ...	0	0	5,000	0	0	0	0	0

Milestones

- | | |
|--|-----------------------|
| 1. Decision on acquisition of second CDC 7600. | April 1976 (Achieved) |
| 2. Complete Network operation. | June 1976 (Achieved) |
| 3. Begin construction of National MFE Computer Center Building (LLL). | Oct. 1976 |
| 4. If decision on second CDC 7600 is positive, installation will occur (LLL). | Nov. 1976 |
| 5. Install mass storage device (LLL). | Jan. 1977 |
| 6. Decision on acquisition of Class VI Computer. | June 1977 |
| 7. Complete construction of National MFE Computer Center building (LLL). | Jan. 1978 |
| 8. If decision on Class VI computer is positive installation will occur (LLL). | early 1978 |

4. Possible Future Experiments

Plasma Properties - Experimental

An experiment not discussed above "A High-Beta Tokamak" is expected to be proposed by Los Alamos Scientific Laboratory in the mid- to late-summer of 1976. An advance copy of the proposal LA-6413-P was received in July 1976. This experiment is designed to utilize the large heating rate inherent in implosion heating for the rapid generation of high-beta tokamak (HBT) plasmas. A study of these plasmas in the proposed HBT machine can give information on how MHD equilibrium and stability limit beta and q. Both a wide current profile and a moderate elongation of the minor cross section has shown to raise the permissible peak beta values in HBT to at least 20%. The longer-term loss processes occurring in MHD-stable plasmas are to be investigated.

The main parameters of the LASL HBT are: $R = 0.30\text{m}$, minor cross sections a racetrack of width, and height 0.24m and 0.48m , $B_T = 20\text{ kG}$, $I_0 = 3\text{ MA}$, $B_0 = 0-12\text{ kG}$ and $I_T \approx 750\text{ kA}$. The projected budget and milestones are given below:

LASL HBT	Projected Budget \$K							
	FY 1976	FY 1976T	FY 1977	FY 1978	FY 1979	FY 1980	FY 1981	FY 1982
Operating	\$ 0	\$ 0	\$ 325	\$ 1,015	\$ 1,100	\$ 1,200	\$ 1,250	\$ 1,300
Equipment	0	0	275	1,235	100	200	200	200
Construction	0	0	0	1,125	0	0	0	

Milestones*

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|--|-----------|
| 1. Complete Major Device Fabrication Review (MDFR) for HBT (LASL). | Nov. 1976 |
| 2. Complete assembly and test of a prototype (LASL). | Feb. 1978 |
| 3. Complete assembly of HBT (LASL). | Jan. 1979 |
| 4. Complete check out and begin initial operation (LASL). | July 1979 |

*Assumes approval of the LASL HBT and the availability of FY 1977 funds.

Exploratory Concepts - Experimental

A preliminary proposal for a Liner Flux Compression experiment has been received from the Los Alamos Scientific Laboratory. The projected budget and milestones are given below.

<u>Fast Liner</u> <u>Experiment</u>	<u>Projected Budget \$K</u>							
	<u>FY 1976</u>	<u>FY 1976T</u>	<u>FY 1977</u>	<u>FY 1978</u>	<u>FY 1979</u>	<u>FY 1980</u>	<u>FY 1981</u>	<u>FY 1982</u>
Operating	\$ 0	\$ 60	\$ 620	\$ 710	\$ 3,300	\$ 3,100	\$ 2,200	\$ 2,500
Equipment	0	0	120	2,650	2,850	275	200	200

Milestones*

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|---|-----------|
| 1. Complete Major Device Fabrication Review (MDFR) for fast liner experiment (LX-1) (IASL). | Oct. 1976 |
| 2. Begin modification of three racks of the Scyllac bank for fast liner experiment (LX-1) (IASL). | July 1976 |
| 3. Begin LX-1 liner experiments on Scyllac bank (IASL). | Feb. 1977 |
| 4. Begin design of fast liner experiment LX-2 (IASL). | Feb. 1978 |
| 5. Complete MDRF for fast liner experiment LX-2 (IASL). | June 1978 |
| 6. Begin construction of LX-2 (IASL). | Nov. 1978 |
| 7. Begin operation of LX-2 (IASL). | Nov. 1980 |

*Assumes approval of the LASL LX-1 and the availability of FY 1977 funds.

NOTE: The required funds for these two proposed LASL experiments are not included in the planned budgets for the Applied Plasma Physics Program at this time. However, funds are available in the planned DMFE budget. Starting one or both of these experiments will depend on the experiments' technical evaluation (MDFR) and the DMFE priorities.

E. Applied Plasma Physics Operating Budget Summary (\$K)

	<u>FY 1976</u>	<u>FY 1976T</u>	<u>FY 1977</u>	<u>FY 1978</u>	<u>FY 1979</u>	<u>FY 1980</u>	<u>FY 1981</u>	<u>FY 1982</u>	<u>Total FY 1978-82</u>
<u>Applied Plasma Physics</u>	<u>\$ 24,300</u>	<u>\$ 7,700</u>	<u>\$ 34,400</u>	<u>\$ 44,100</u>	<u>\$ 48,000</u>	<u>\$ 55,000</u>	<u>\$ 55,000</u>	<u>\$ 55,000</u>	<u>\$257,100</u>
<u>Fusion Plasma Theory</u>	<u>12,300</u>	<u>3,600</u>	<u>13,600</u>	<u>17,700</u>	<u>21,000</u>	<u>25,000</u>	<u>25,000</u>	<u>25,000</u>	<u>113,700</u>
Plasma Properties	5,000	1,440	5,310	5,630	7,000	8,200	8,300	8,400	37,530
Plasma Production and Heating	500	140	520	1,000	1,220	1,480	1,500	1,500	6,700
Atomic, Molecular and Nuclear Physics	330	100	470	820	990	1,100	1,000	850	4,750
Exploratory Concepts	0	0	0	1,250	1,290	1,420	1,350	1,250	6,560
Computer Applications	6,470	1,920	7,300	9,000	10,500	12,800	12,850	13,000	58,150
<u>Experimental Plasma Research</u>	<u>8,800</u>	<u>3,100</u>	<u>15,800</u>	<u>17,400</u>	<u>18,300</u>	<u>20,000</u>	<u>20,000</u>	<u>20,000</u>	<u>95,700</u>
Plasma Properties	1,590	725	2,125	2,300	2,700	2,800	2,500	2,300	12,600
Plasma Production and Heating	2,660	735	2,380	2,400	2,600	2,800	2,600	2,500	12,900
Measurements and Instrumentation....	1,060	340	2,100	2,735	2,950	3,100	2,900	2,700	14,385
Atomic, Molecular and Nuclear Physics	1,290	445	2,000	2,700	3,100	3,500	3,600	3,500	16,400
Fusion Plasma Research Facility.....	0	0	3,000	3,000	2,500	2,600	2,700	2,800	13,600
Exploratory Concepts	2,200	855	4,195	4,265	4,450	5,200	5,700	6,200	25,815
<u>Computer Services and Technology</u>	<u>3,200</u>	<u>1,000</u>	<u>5,000</u>	<u>9,000</u>	<u>8,700</u>	<u>10,000</u>	<u>10,000</u>	<u>10,000</u>	<u>47,700</u>

